3 1176 00140 1653

NASA CR-159,174

NASA Contractor Report 159174

NASA-CR-159174
1980 0011820

TECHNOLOGY REQUIREMENTS FOR FUTURE
EARTH-TO-GEOSYNCHRONOUS ORBIT TRANSPORTATION
SYSTEMS

VOLUME III: APPENDICES

Vincent A. Caluori, Robert T. Conrad,
and James C. Jenkins

BOEING AEROSPACE COMPANY
Seattle, Washington 98124

NASA Contract NAS1-15301
March 1980

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23665

CONTENTS

N 80-20303 #

APPENDIX A

ENGINE DATA

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF TABLES

LIST OF TABLES (Continued)

1.0 INTRODUCTION

This appendix provides detail technical engine data for the SSTO, HLLV, and POTV vehicles. These data are the results of Aerojet Liquid Rocket Company subcontract N-500601-9109 to prime contract NAS1-15301. Engine data is organized by the following sections.

Section 2.0	Mode I LOX/Methane Engine Parametric Data (Sea-Level thrust - 1.8 x 10^6N to 4 x 10^6N (400,000 to 900,000 lb) Chamber pressure - - 13,800 to 34,500 kPa (2,000 to 5,000 psia) Nozzle area ratio - 20:1 to 60:1
Section 3.0	LOX/Methane Engine Parametric Data (Sea-Level thrust - 4.5 x 10^6 N to 11.1 x 10^6 N (1,000,000 to 2,500,000 lb) Chamber pressure - 13,800 to 34,500 kPa (2,000 to 5,000 psia) Nozzle area ratio - 40:1 to 60:1
Section 4.0	Advanced Technology Forecast (1. Dual Expander engine parametric data; 2. Integrated Thruster Assembly Performance Data; 3. Plug Cluster Engine performance data; and 4. Propulsion Growth projections)
Section 5.0	Engine Consulting Data (1. PCE, 40,000 lb thrust; 2. LOX/CH_4 70:30: LOX/LH_2 Dual Expander Engine; and 3. Throttled 70:30 Dual Expander Engine)
Section 6.0	References

2.0 MODE I LOX/CH_4 ENGINE

This technical brief presents the parametric performance, weight and envelope data for the LOX/CH_4, fuel cooled, staged combustion cycle and the hydrogen cooled, expander bleed cycle engine concepts.

2.1 PARAMETRIC PERFORMANCE, WEIGHT AND ENVELOP DATA

The Mode I LOX/CH_4 engines are defined by the schematics shown on figures 2-1 and 2-2. For these engine concepts, engine weight and envelope data were established for the following variables and ranges:

Sea-Level Thrust	-	1.8×10^6N to 4×10^6N (400,000 to 900,000 lbf)
Chamber Pressure	-	13,800 to 34,500 kPa (2,000 to 5,000 psia)
Nozzle Area Ratio	-	20:1 to 60:1

A fixed 90% bell nozzle was assumed.

The elements of engine weight included in the parametric analysis are defined on table 2-1. Those items not included in the weight data are also listed. LOX/CH_4 weight statements are given on tables 2-2 and 2-3.

The engine weight data is presented on figures 2-3 through 2-5. The engine length and diameter parametrics are presented on figures 2-6 through 2-13. The engine performance summaries are given on tables 2-4 and 2-5, and performance parametrics are given on figures 2-11 through 2-16.

Normal growth projections are given on table 2-6.

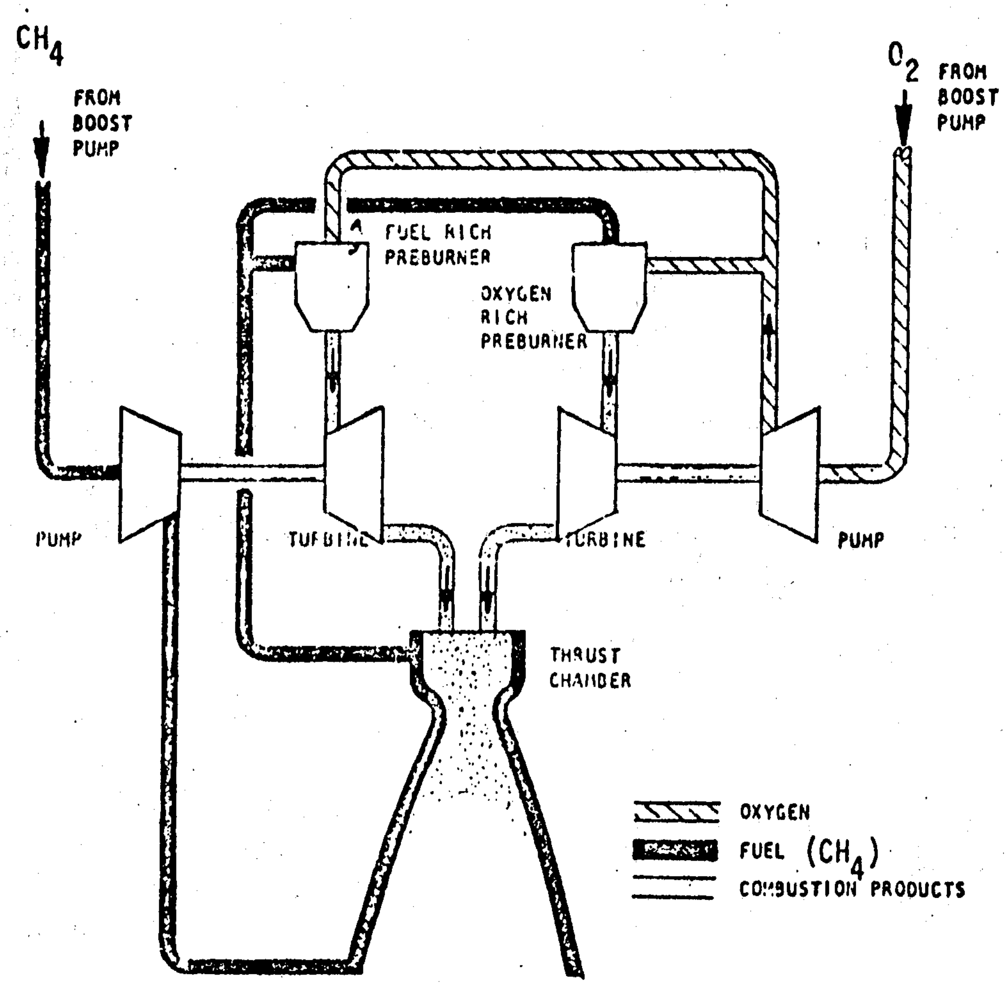


Figure 2-1. Mode I Fuel Cooled Engine Cycle Schematic

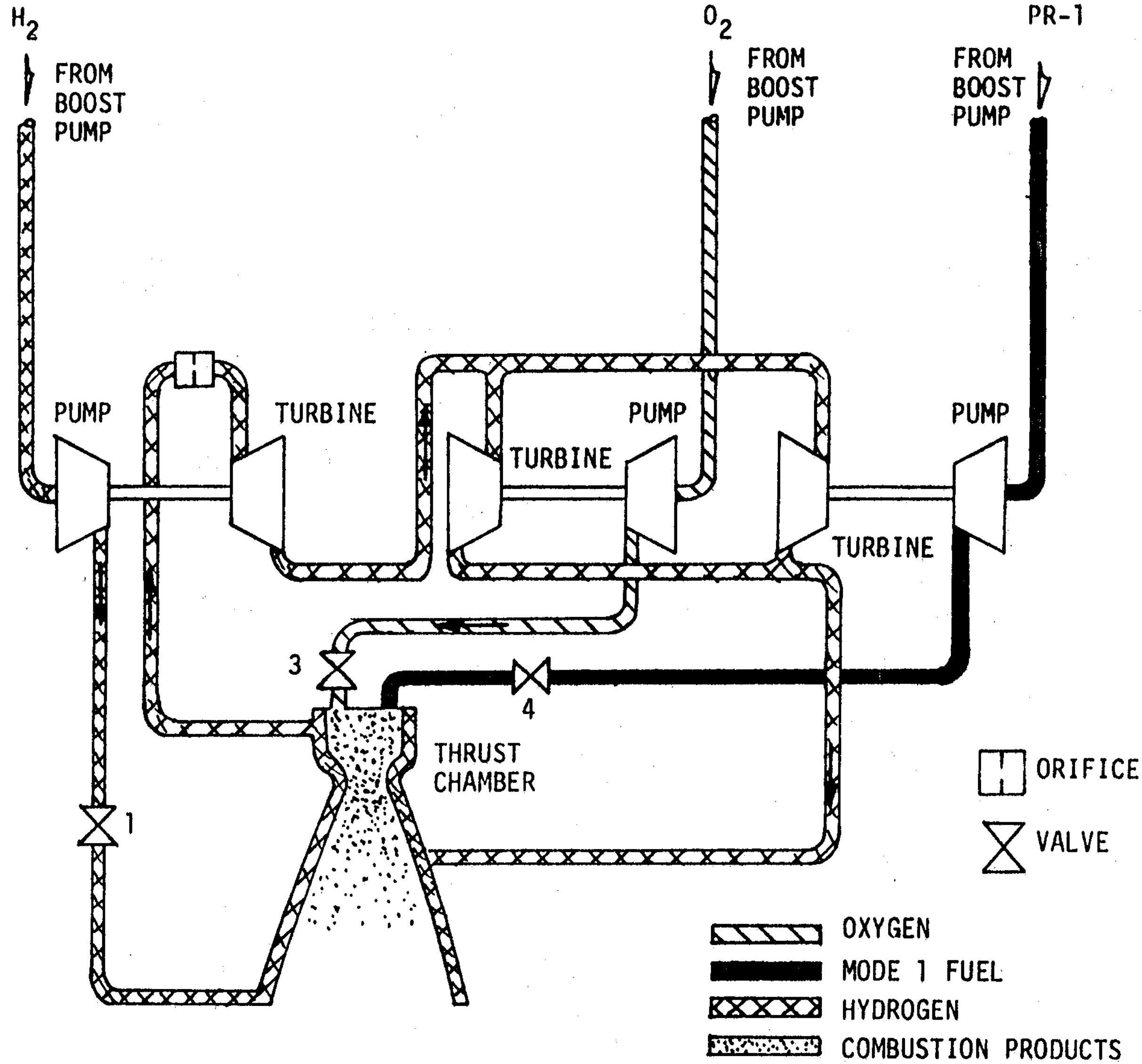


Figure 2-2. Mode I Hydrogen Cooled, Expander Bleed Cycle Schematic

Table 2-1. LOX/CH_4 Engine Weight Definition

For purposes of the parametric weight study, the engine is assumed to be composed of the following components:

- o Regeneratively Cooled Combustion Chamber
- o Regeneratively Cooled Thrust Chamber Fixed Nozzle
- o Main Injector
- o Main Turbopumps
- o Boost Pumps
- o Preburners (Not Used For Expander Bleed Cycle)
- o Propellant Valves and Actuation
- o Gimbal
- o Hot Gas Manifold (Not Used For Expander Bleed Cycle)
- o Propellant Lines
- o Ignition System
- o Miscellaneous (Electrical Harness, Instrumentation, Brackets, Auxiliary Lines and Controls)

Engine dry weights do not include:

- o Gimbal Actuators and Actuation System
- o Engine Controller
- o Pre-Valves
- o Tank Pressurant Heat Exchangers and Associated Equipment
- o Contingency (A Total Contingency is Normally Included in the Vehicle Weight Statement)

Table 2-2. LOX/CH_4 Baseline Engine Weight Statement Staged Combustion Cycle

F_{SL} = 607,000 lb.

P_c = 4,000 psia

ε = 40

Component	Weight, Lb.
Gimbal	209
Main Injector	597
Main Chamber	281
Nozzle	550
Fuel Preburner	135
Ox. Preburner	132
Ox. Valves and Actuation	442
Fuel Valves and Actuation	148
Ox. Boost Pump	159
Fuel Boost Pump	174
Main Ox. Pump	761
Main Fuel Pump	528
Hot Gas Manifold	170
Low Pressure Lines	195
High Pressure Lines	259
Ignition System	60
Miscellaneous	442
Total	5,242
Sea-Level Thrust/Weight	116

Table 2-3. Mode 1 LOX/CH_4 Hydroben Hydrogen Cooled, Expander Bleed Cycle Engine Weight Statement

F_{SL} = 607,000 lb.

P_c = 4,250

ε = 40

Component	Weight, Lb
Gimbal	211
Main Injector	769
Copper Chamber and Nozzle (ε = 25)	351
Tube Bundle Nozzle (ε = 25 to 40)	193
Fuel Valves and Actuation	150
Oxidizer Valves and Actuation	166
Low Speed LOX TPA	306
Low Speed CH_4 TPA	81
Low Speed LH_2 TPA	17
High Speed LOX TPA	599
High Speed CH_4 TPA	281
High Speed LH_2 TPA	125
Low Pressure Lines	189
High Pressure Lines	238
Ignition System	60
Miscellaneous	442
Total	4,178
Sea-Level Thrust/Weight	145

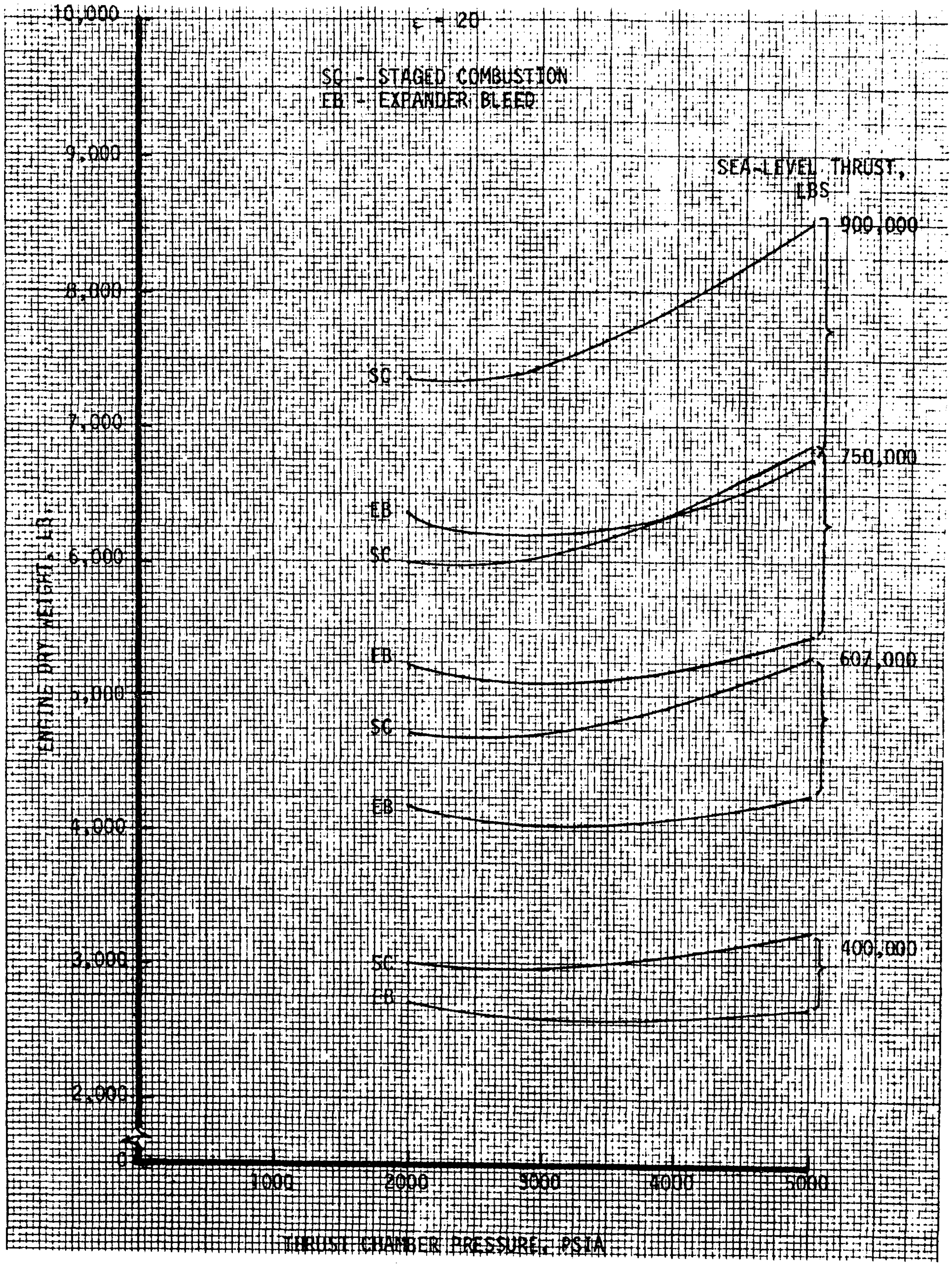


Figure 2-3. Mode I LOX/CH_4 Engine Weight Parametrics

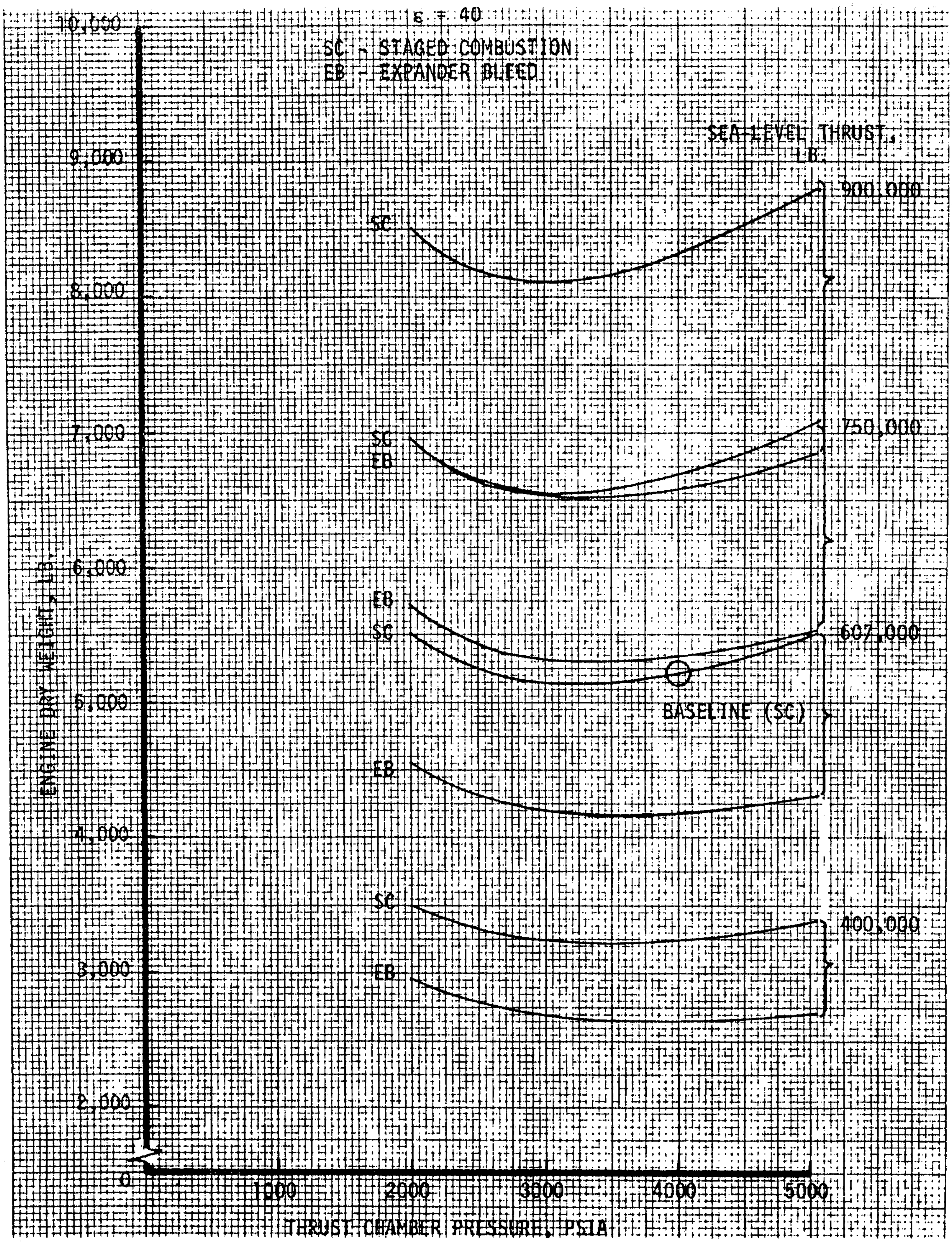


Figure 2-4. Mode I LOX/CH_4 Engine Weight Parametrics

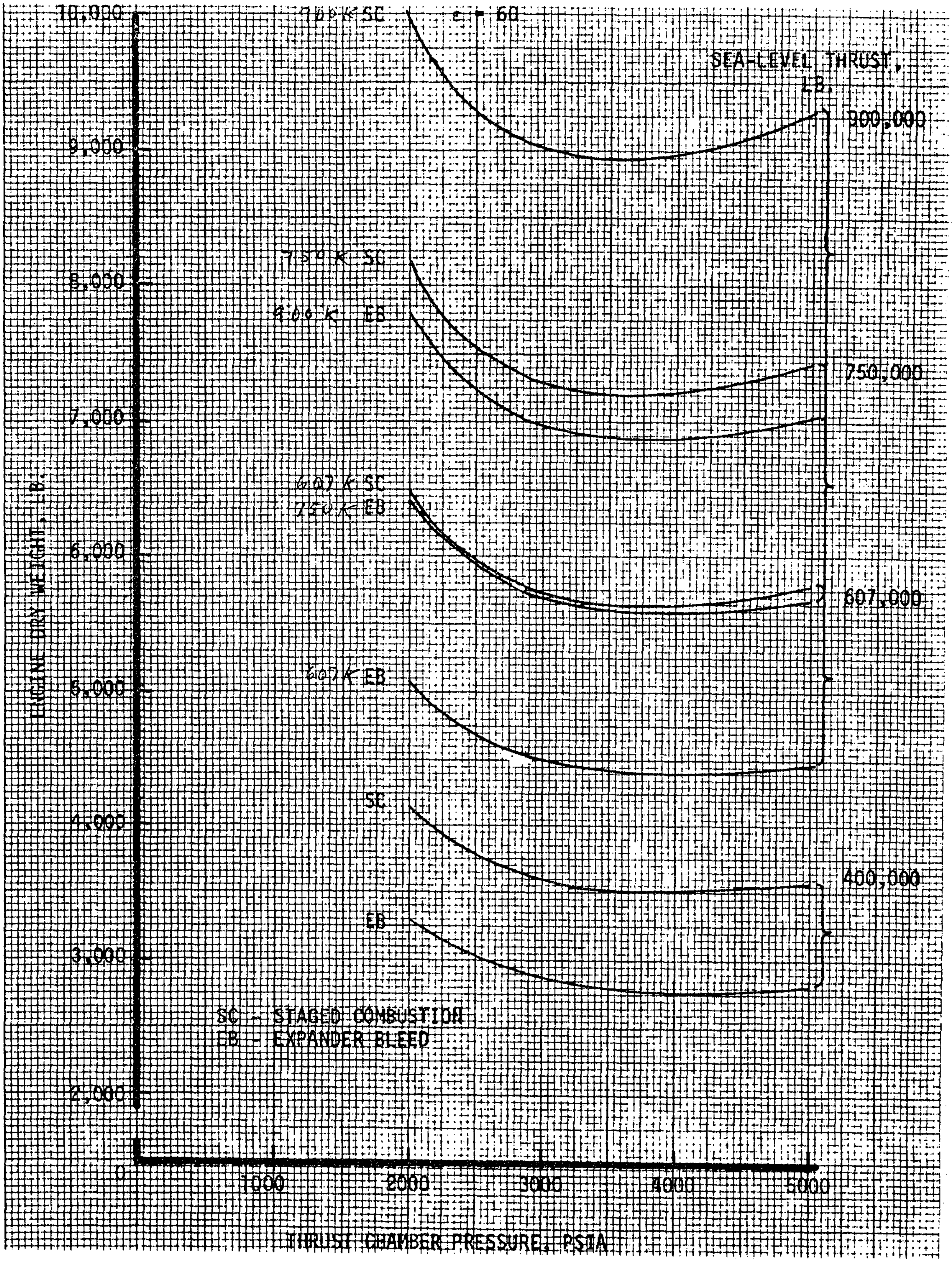


Figure 2-5. Mode I LOX/CH_4 Engine Weight Parametrics

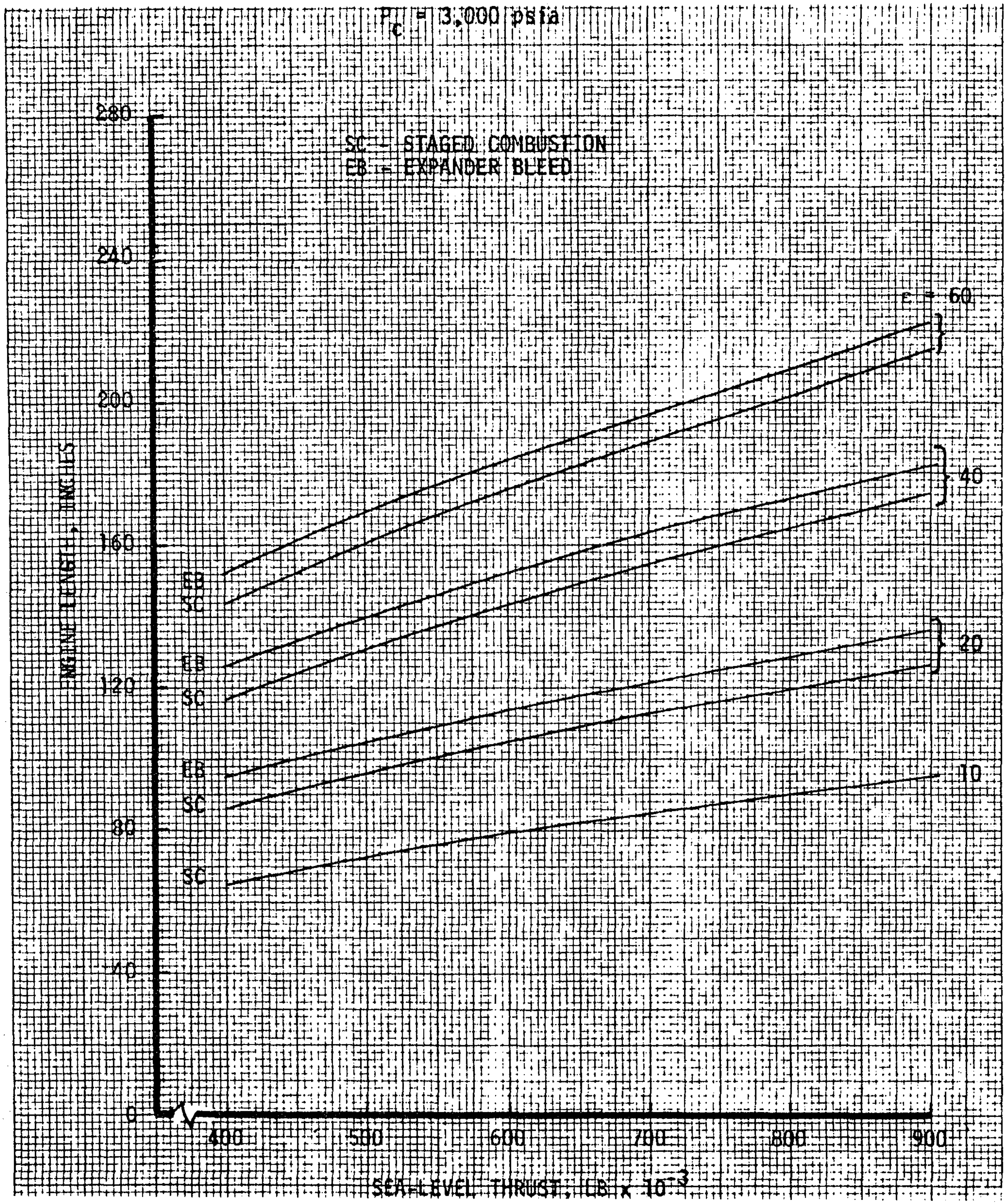


Figure 2-7. Mode I LOX/CH_4 Engine Length vs Sea-Level Thrust

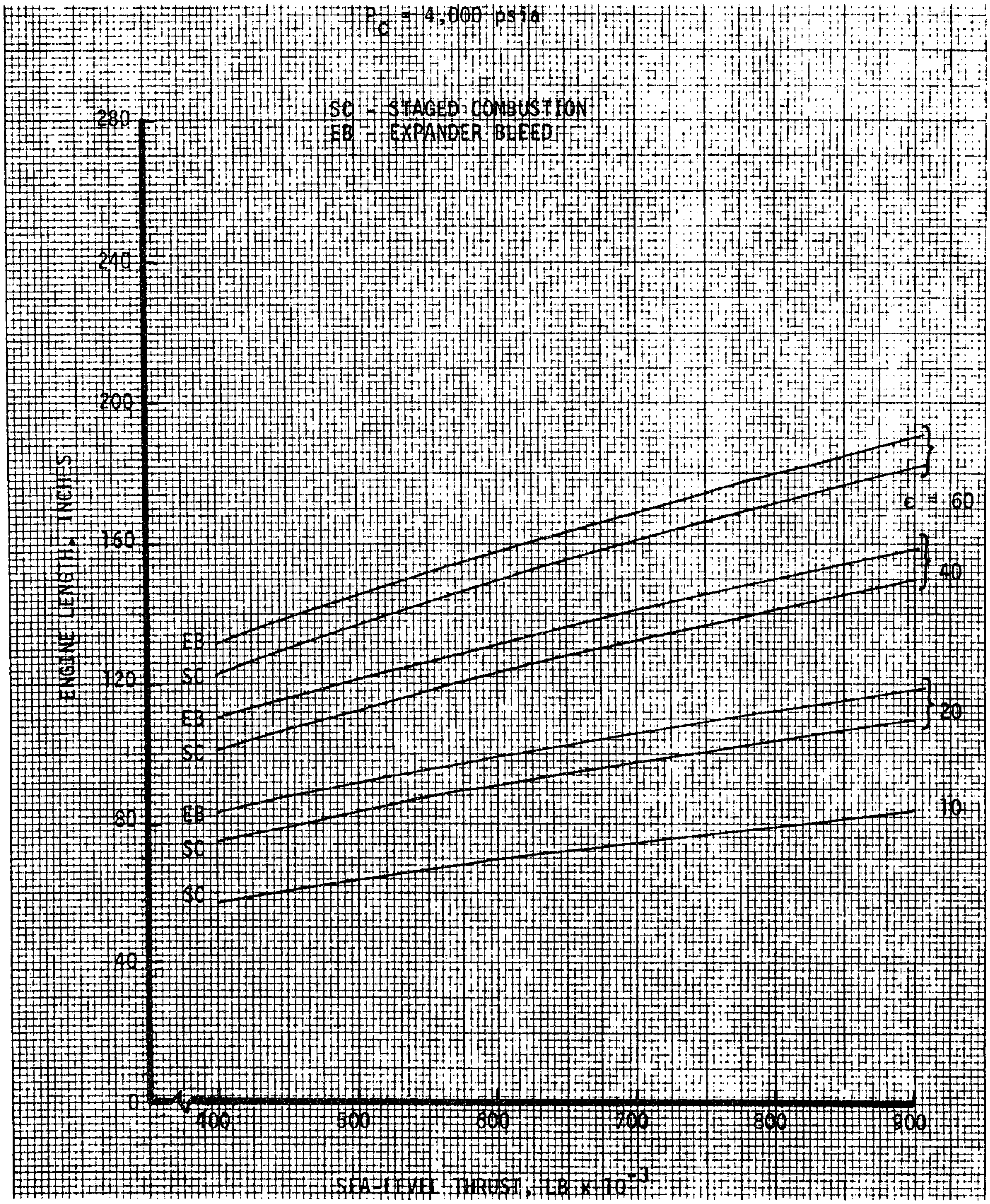


Figure 2-8. Mode I LOX/CH_4 Engine Length vs Sea-Level Thrust

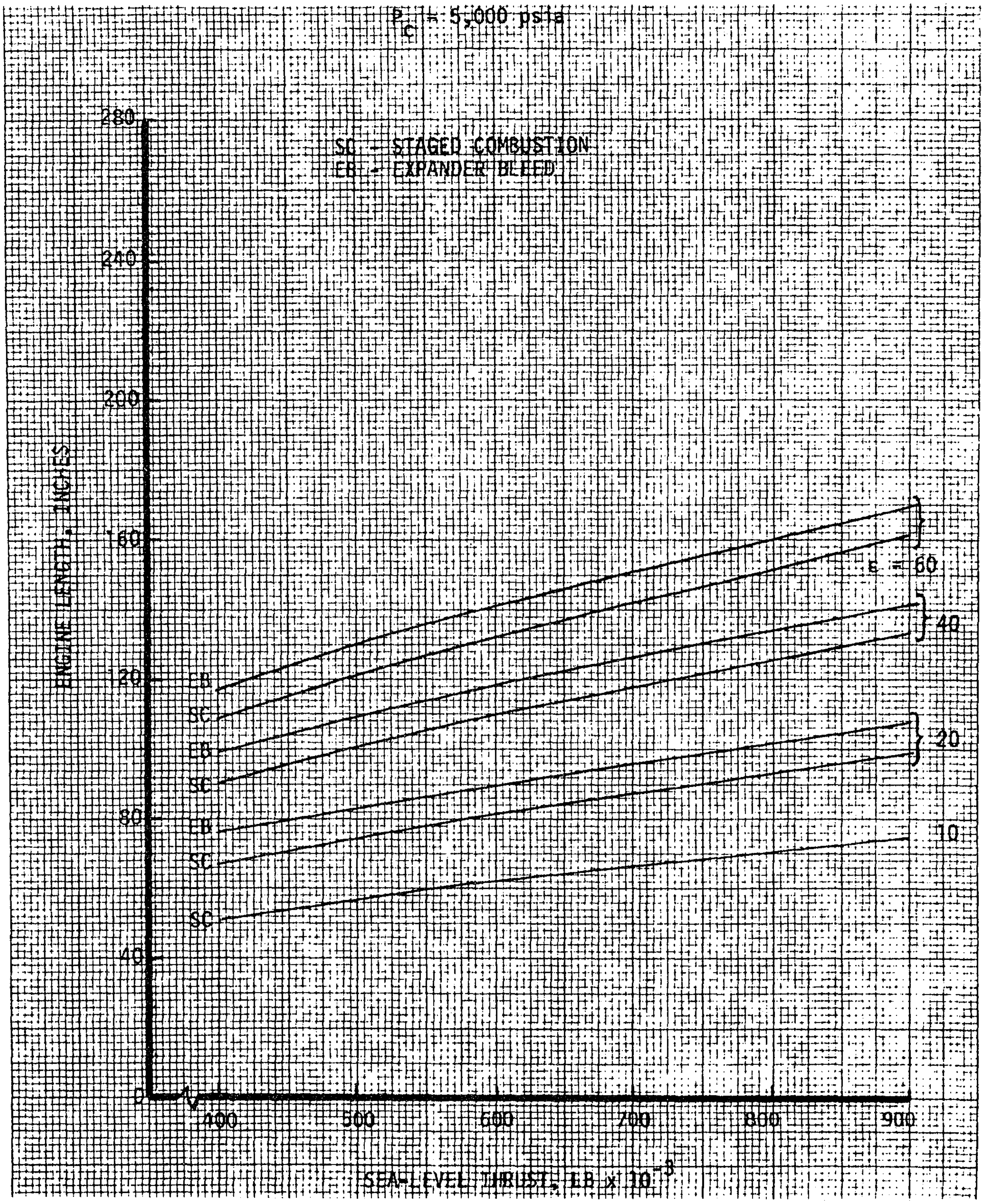


Figure 2-9. Mode I LOX/CH_4 Engine Length vs Sea-Level Thrust

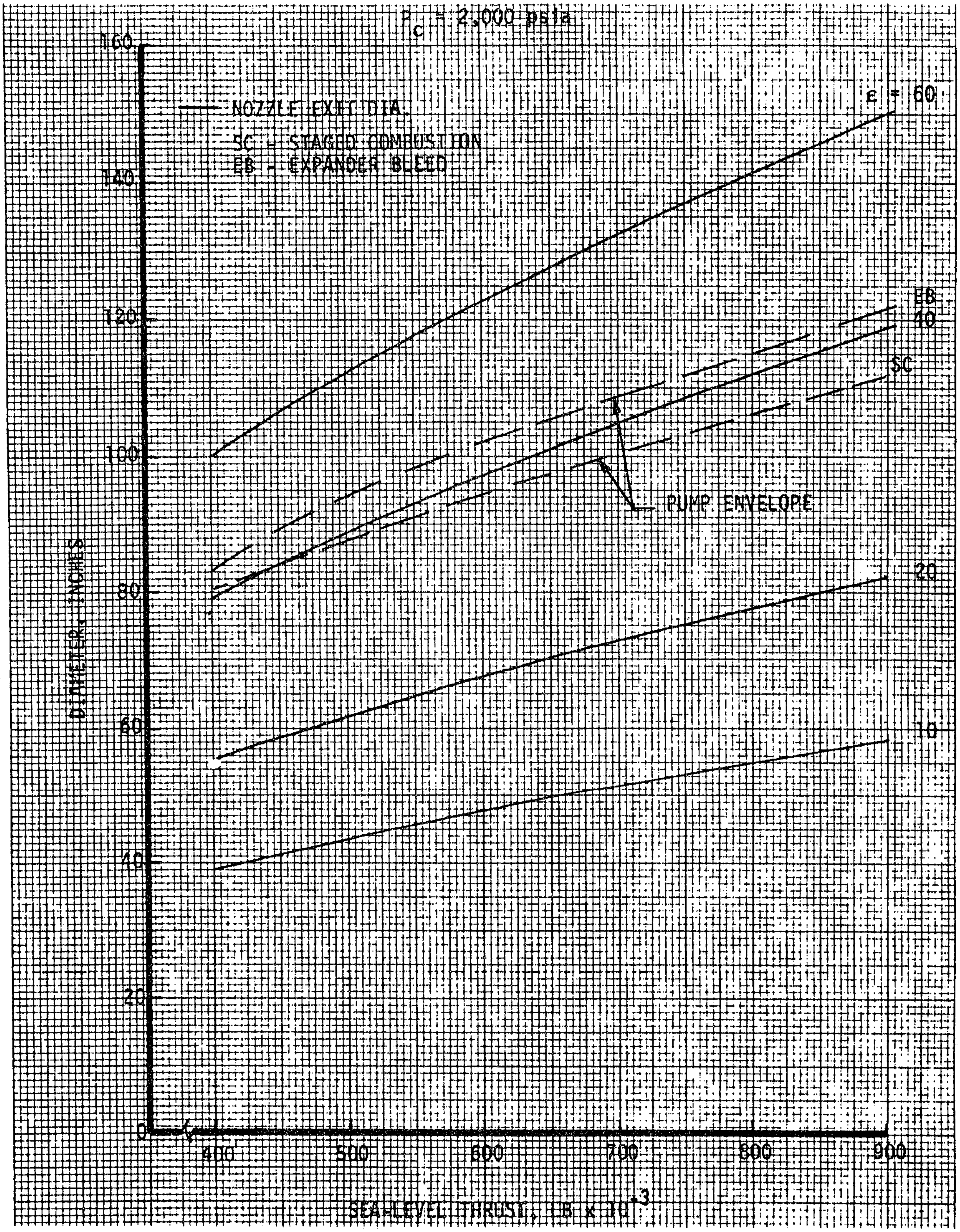


Figure 2-10. Mode I LOX/CH_4 Engine Diameter Parametrics

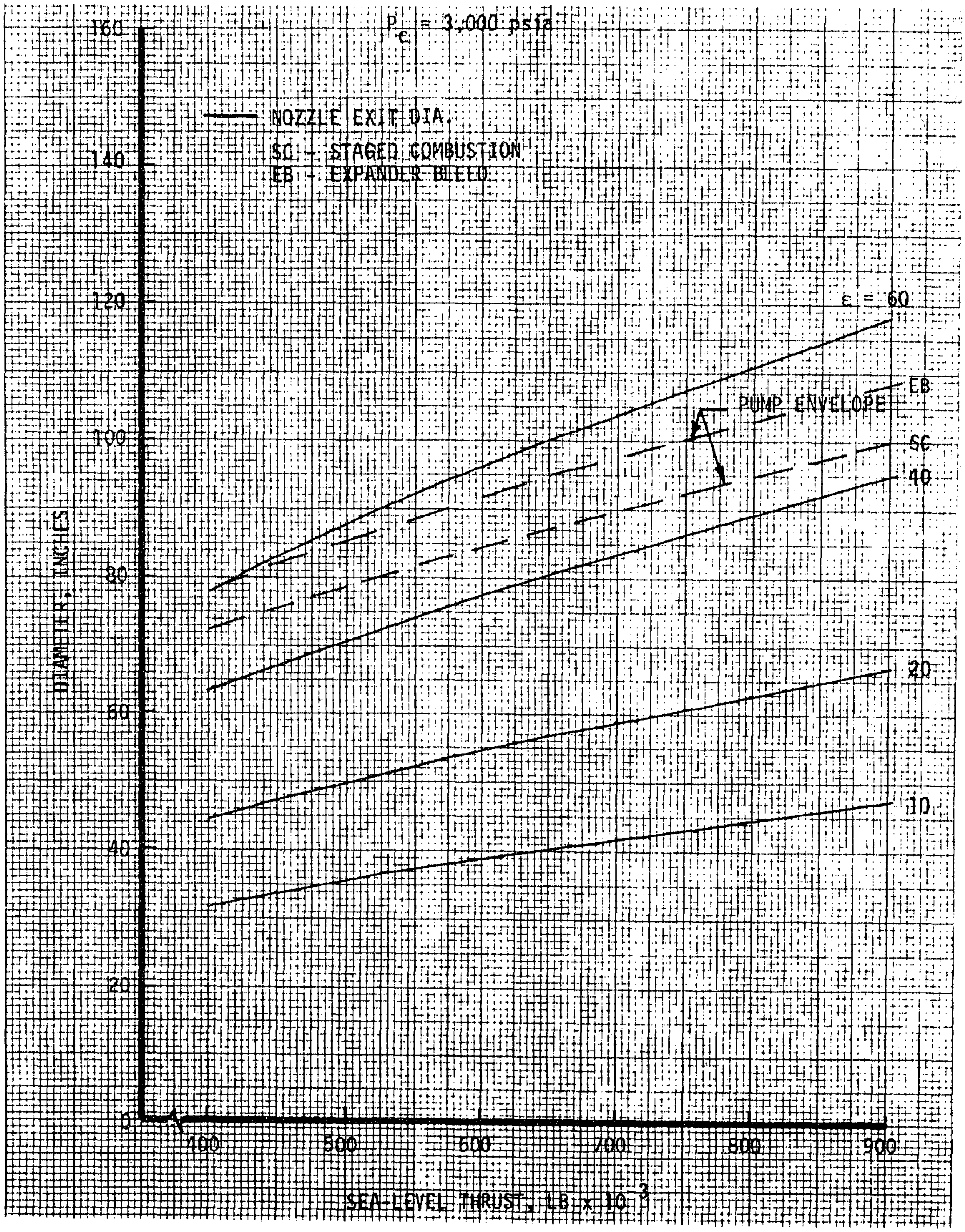


Figure 2-11. Mode I LOX/CH_4 Engine Diameter Parametrics

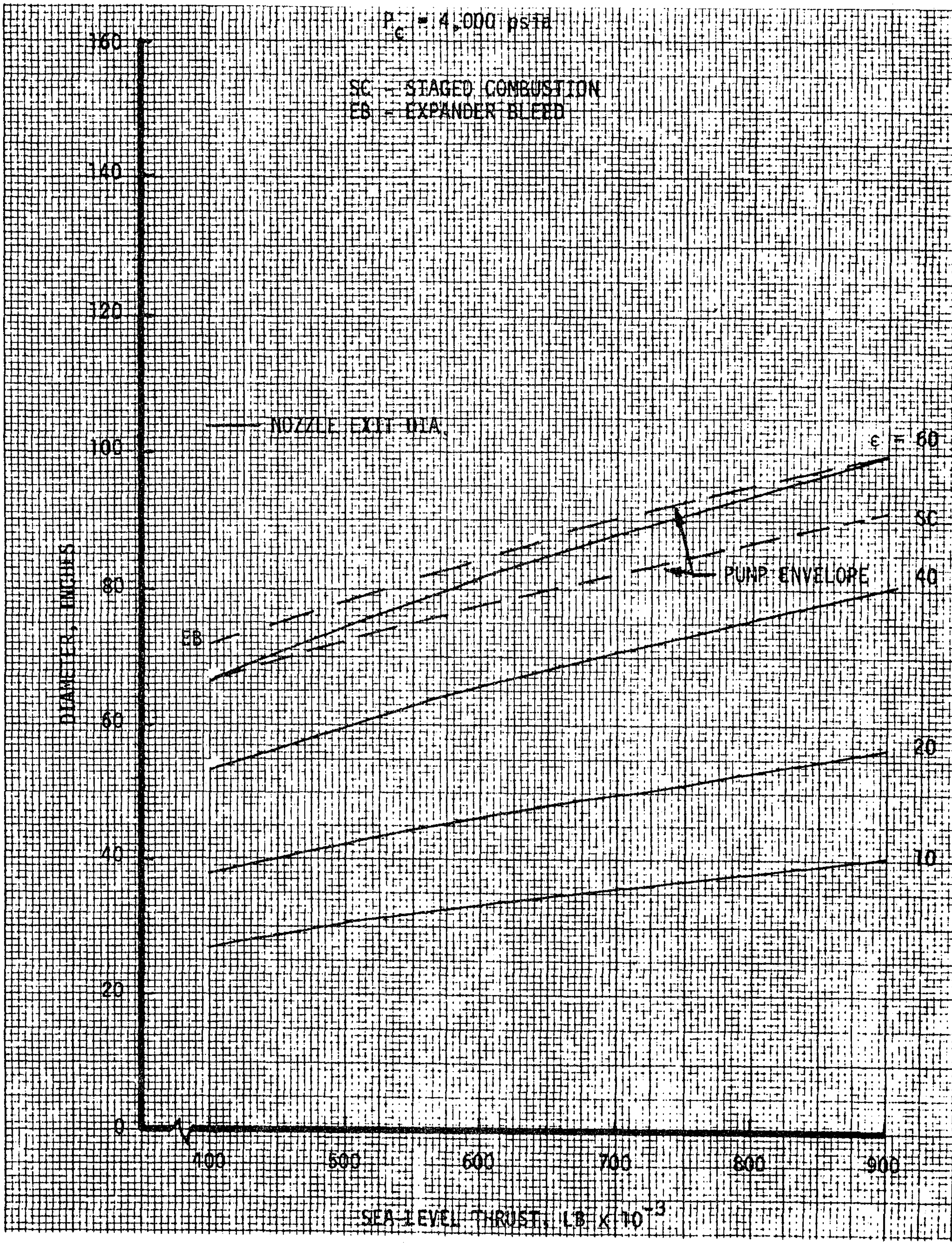


Figure 2-12. Mode I LOX/CH_4 Engine Diameter Parametrics

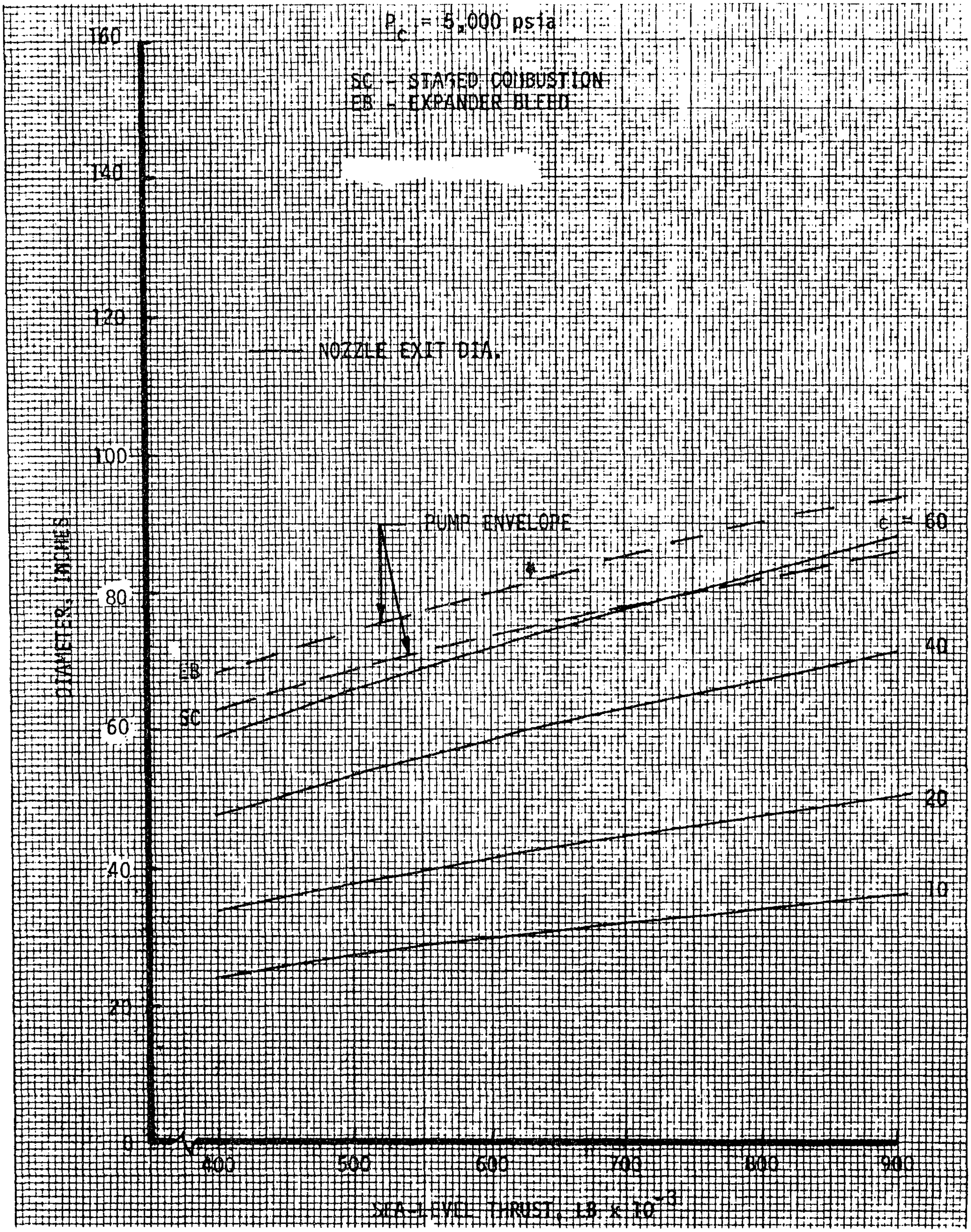


Figure 2-13. Mode I LOX/CH_4 Engine Diameter Parametrics

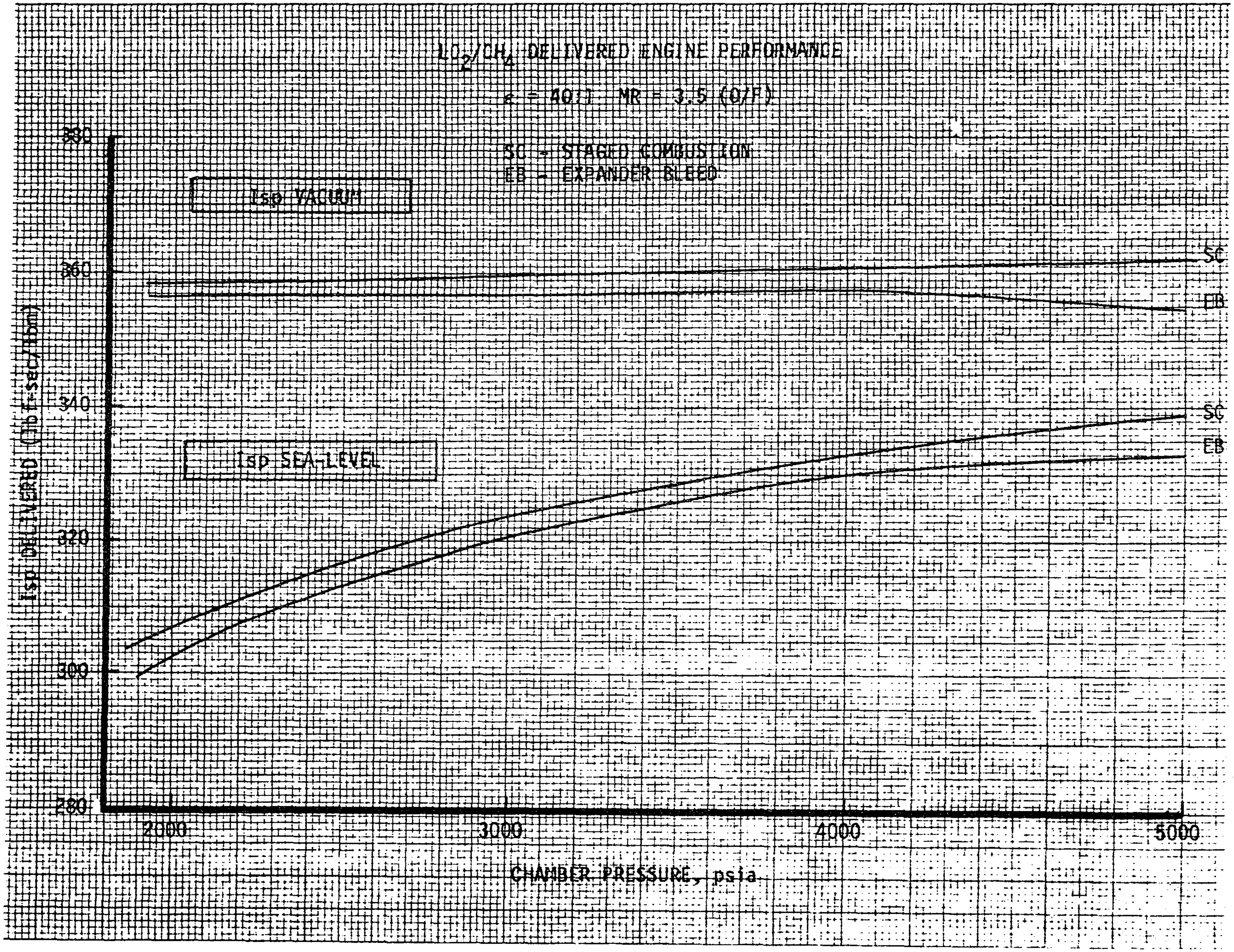


Figure 2-14. LO_2/CH_4 Delivered Engine Performance

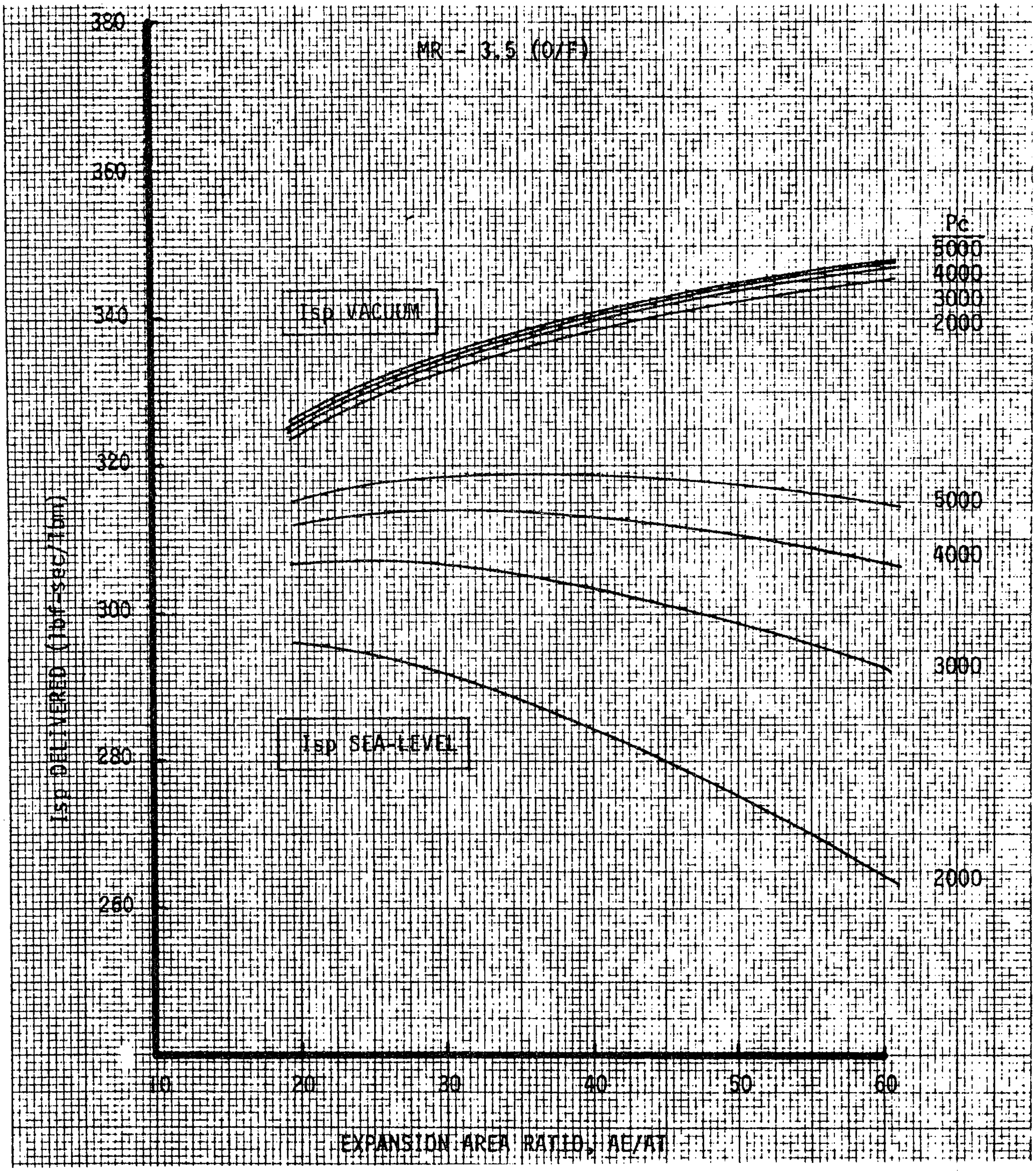


Figure 2-15. LO_2/CH_4 Staged Combustion Delivered Performance vs Area Ratio (AE/AT)

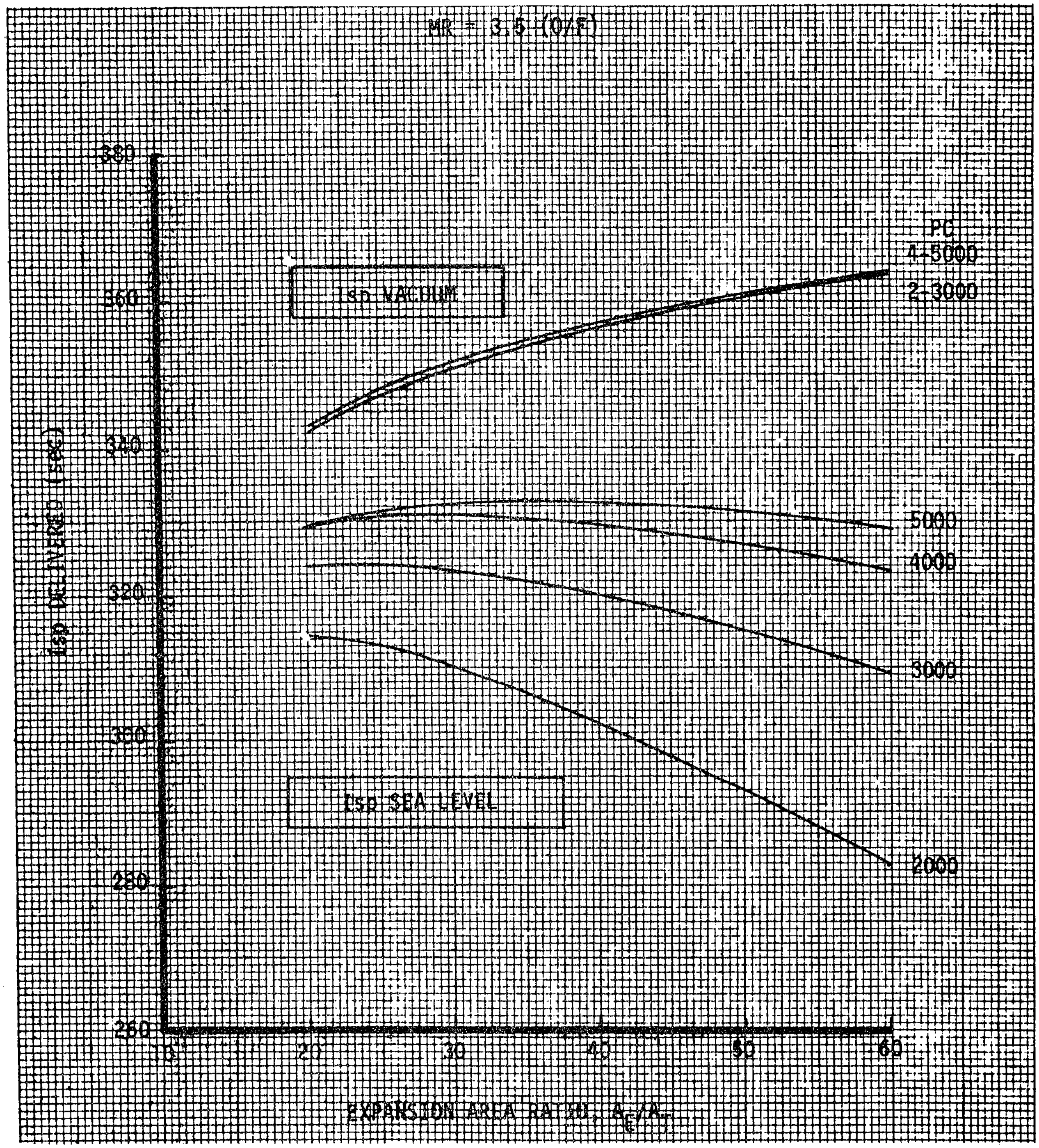


Figure 2-16. LOX/CH_4 Expander Bleed Delivered Performance vs Area Ratio

Table 2-4. LO_2/CH_4 Staged Combustion Performance Summary

(MR = 3.5, ε = 40:1, r_t = 5.190 in, ε_c = 2.5, 80% Bell Nozzle)

Pc (psia)	2000	3000	4000	5000
ODE Vacuum Isp (sec)	370.2	371.0	371.5	371.8
ΔIsp_{KL}	1.5	1.2	1.1	1.0
ODK Vacuum Isp (sec)	368.7	369.8	370.4	370.8
ΔIsp_{ERL} (1.5% ODK)	5.5	5.5	5.6	5.6
ΔIsp_{DL} (.65% ODK)	2.4	2.4	2.4	2.4
ΔIsp_{BL}	2.0	2.0	2.0	2.0
Delivered Vacuum Isp (sec)	358.8	359.9	360.4	360.8
Sea-Level Isp Correction	54.3	36.3	27.3	21.9
Delivered Sea-Level Isp (sec)	304.5	323.6	333.1	338.9

Table 2-5. LO_2/CH_4 Expander Bleed Performance Summary

(MR = 3.5, ε = 40:1, 80% Bell Nozzle)

Pc (psia)	2000	3000	4000	5000
ODE Vacuum Isp (sec)	370.2	371.0	371.5	371.8
ΔIsp_{KL}	1.5	1.2	1.1	1.0
ODK Vacuum Isp (sec)	368.7	369.8	370.4	370.8
ΔIsp_{ERL} (1.5% ODK)	5.5	5.5	5.6	5.6
ΔIsp_{DL} (.65% ODK)	2.4	2.4	2.4	2.4
ΔIsp_{BL}	2.0	2.0	2.0	2.0
ΔIsp^{*}_{HL}	1.2	1.2	1.2	1.2
ΔIs^{**}_{CL}	0.9	2.0	3.0	5.0
Delivered Vacuum Isp (sec)	356.7	356.7	357.2	354.6
Sea-Level Isp Correction	54.3	36.3	27.3	21.9
Delivered Sea-Level Isp (sec)	302.4	320.4	329.9	332.7

* Heat Loss to Hydrogen Coolant

** Coolant Bleed Loss

Table 2-6. LOX/CH_4 Engine Normal Growth Projections

	Present Value (1978)	Change	Projected Value (1995)
1. Increase vacuum specific impulse (sec)	357.3	$8.7 \begin{smallmatrix}+1 \\ -2\end{smallmatrix}$	$366.0 \begin{smallmatrix}+1 \\ -2\end{smallmatrix}$
2. Increase sea level specific impulse (sec)	332.1	$8.1 \begin{smallmatrix}+1 \\ -3\end{smallmatrix}$	$340.2 \begin{smallmatrix}+1 \\ -3\end{smallmatrix}$
3. Decrease engine weight (lb) through advanced structures	4178	$836 \begin{smallmatrix}+100 \\ -210\end{smallmatrix}$	$3342 \begin{smallmatrix}+210 \\ -100\end{smallmatrix}$
4. Increase engine thrust/weight ratio at sea level (lb_f/lb_m)	145	$41 \begin{smallmatrix}+6 \\ -12\end{smallmatrix}$	$186 \begin{smallmatrix}+6 \\ -12\end{smallmatrix}$
5. Reduce engine length (in)	132	$50 \begin{smallmatrix}+10 \\ -20\end{smallmatrix}$	$82 \begin{smallmatrix}+20 \\ -10\end{smallmatrix}$
6. Reduce engine diameter (in)	85	$15 \begin{smallmatrix}+2 \\ -6\end{smallmatrix}$	$70 \begin{smallmatrix}+6 \\ -2\end{smallmatrix}$

3.0 LOX/CH_4 EXPANDER BLEED CYCLE ENGINE

This section contains technical information on the parametric performance, weight and envelope data for the LOX/CH_4 expander bleed cycle engine concept.

3.1 EXPANDER BLEED CYCLE PARAMETRIC PERFORMANCE, WEIGHT AND ENVELOPE DATA

Engine weight and envelop data are established for the following variables and ranges:

Sea-Level Thrust	- 4.5×10^6N to 11.1×10^6N (1,000,000 to 2,500,000 lb)
Chamber Pressure	- 13,800 to 34,500 kPa (2,000 to 5,000 psia)
Nozzle Area Ratio	- 40:1 and 60:1

The engine weight data are given in figures 3-1 and 3-2. Engine length and diameter parametrics are given in figures 3-3 through 3-8. For ready comparison of the engines, figures 3-9 and 3-10 show the trend in engine thrust-to-weight ratio as a function of chamber pressure and engine thrust level.

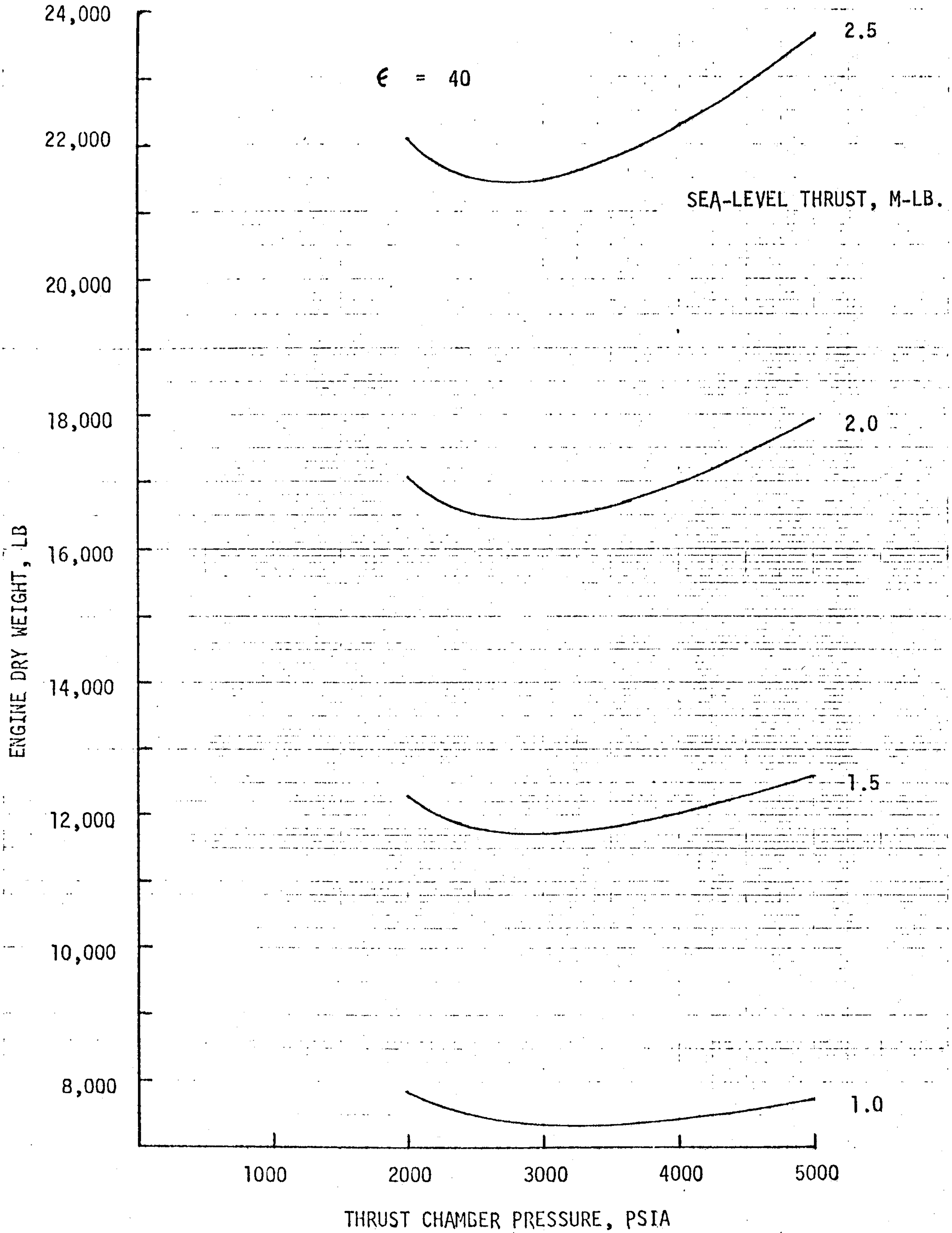


Figure 3-1. Mode I LOX/CH_4 Engine Weight Parametrics, Expander Bleed Cycle

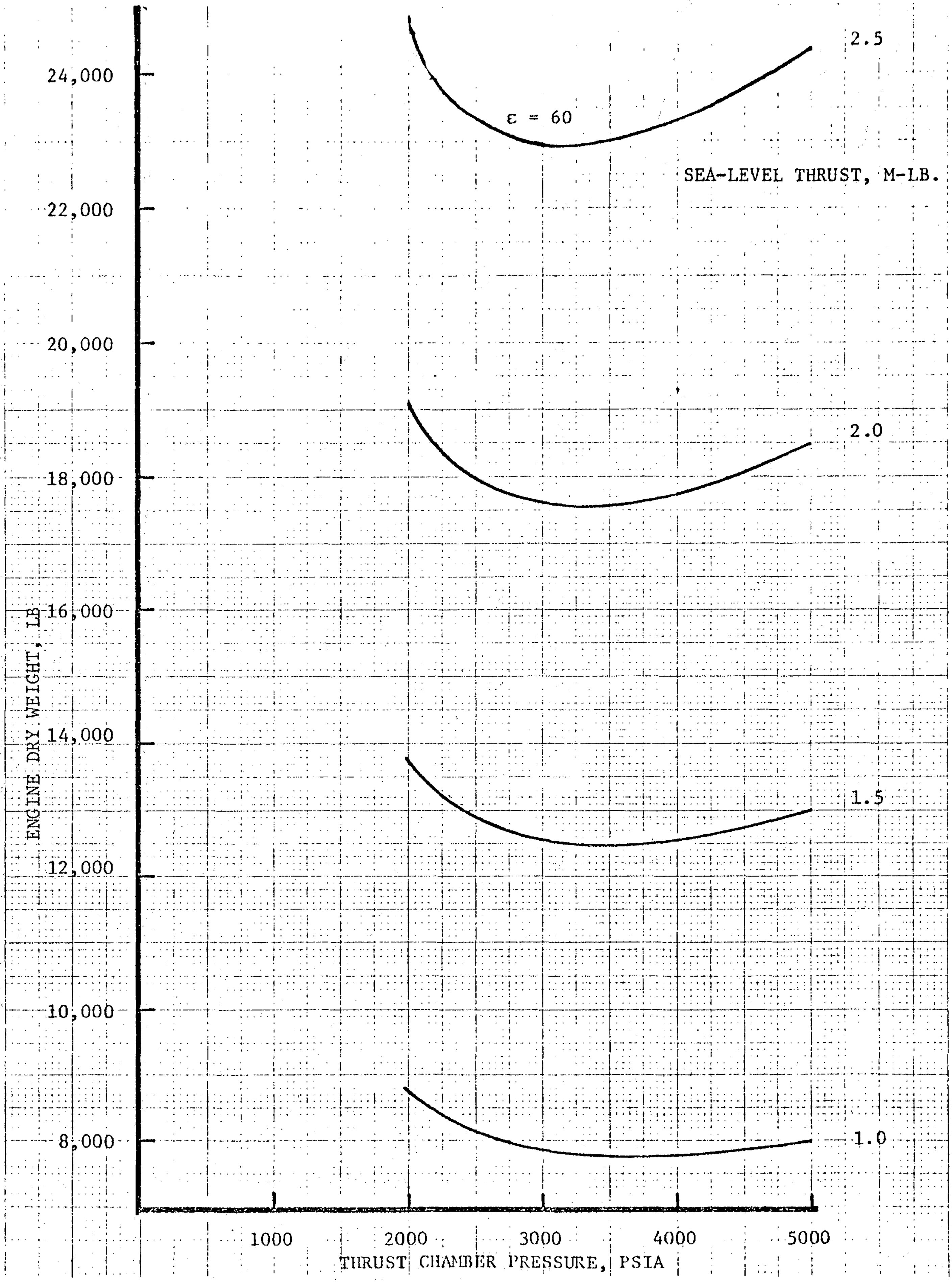


Figure 3-2. Mode I LOX/CH_4 Engine Weight Parametrics, Expander Bleed Cycle

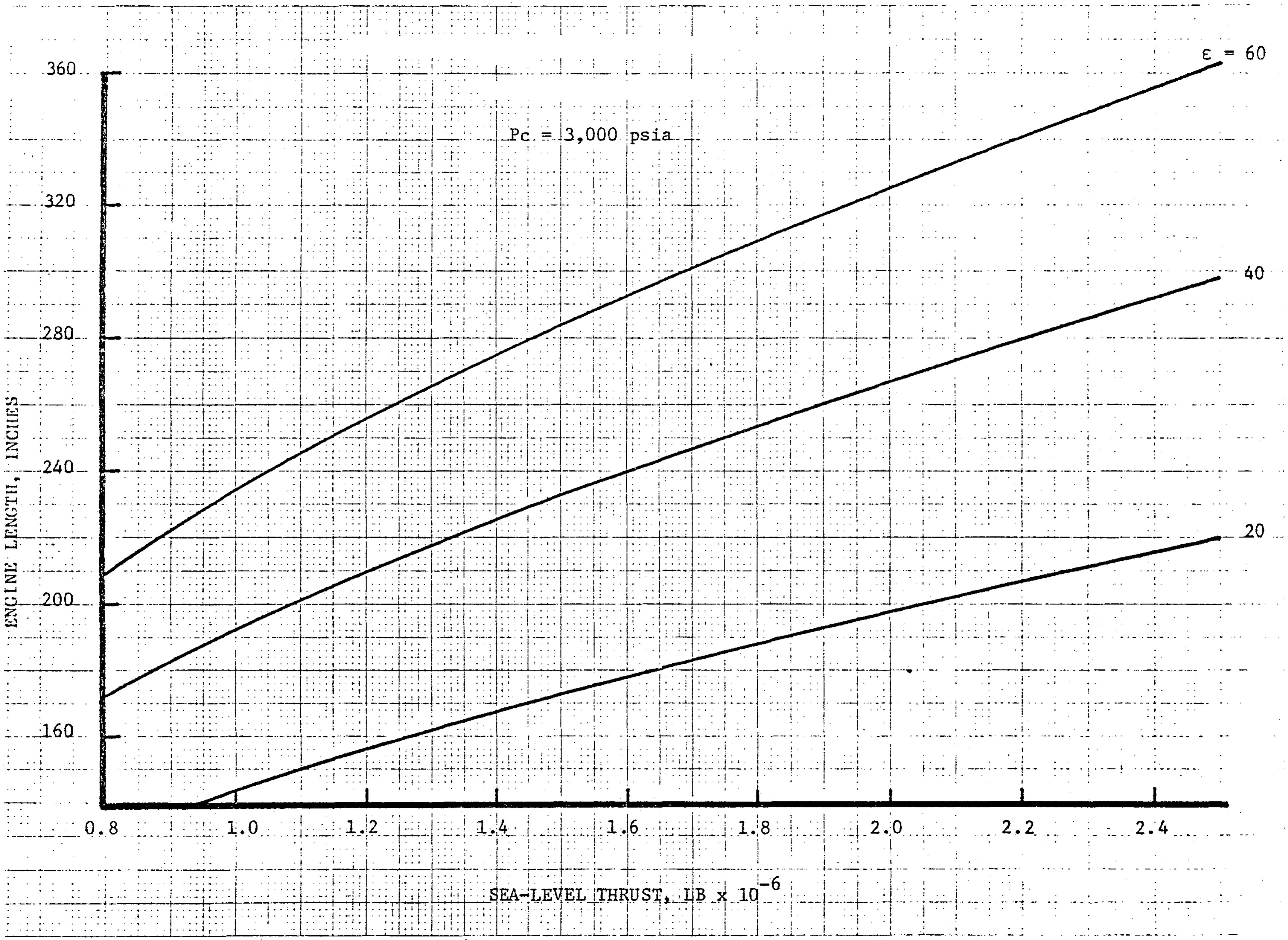


Figure 3-3. Mode I LOX/CH_4 Engine Length vs Sea-Level Thrust, Expander Bleed Cycle

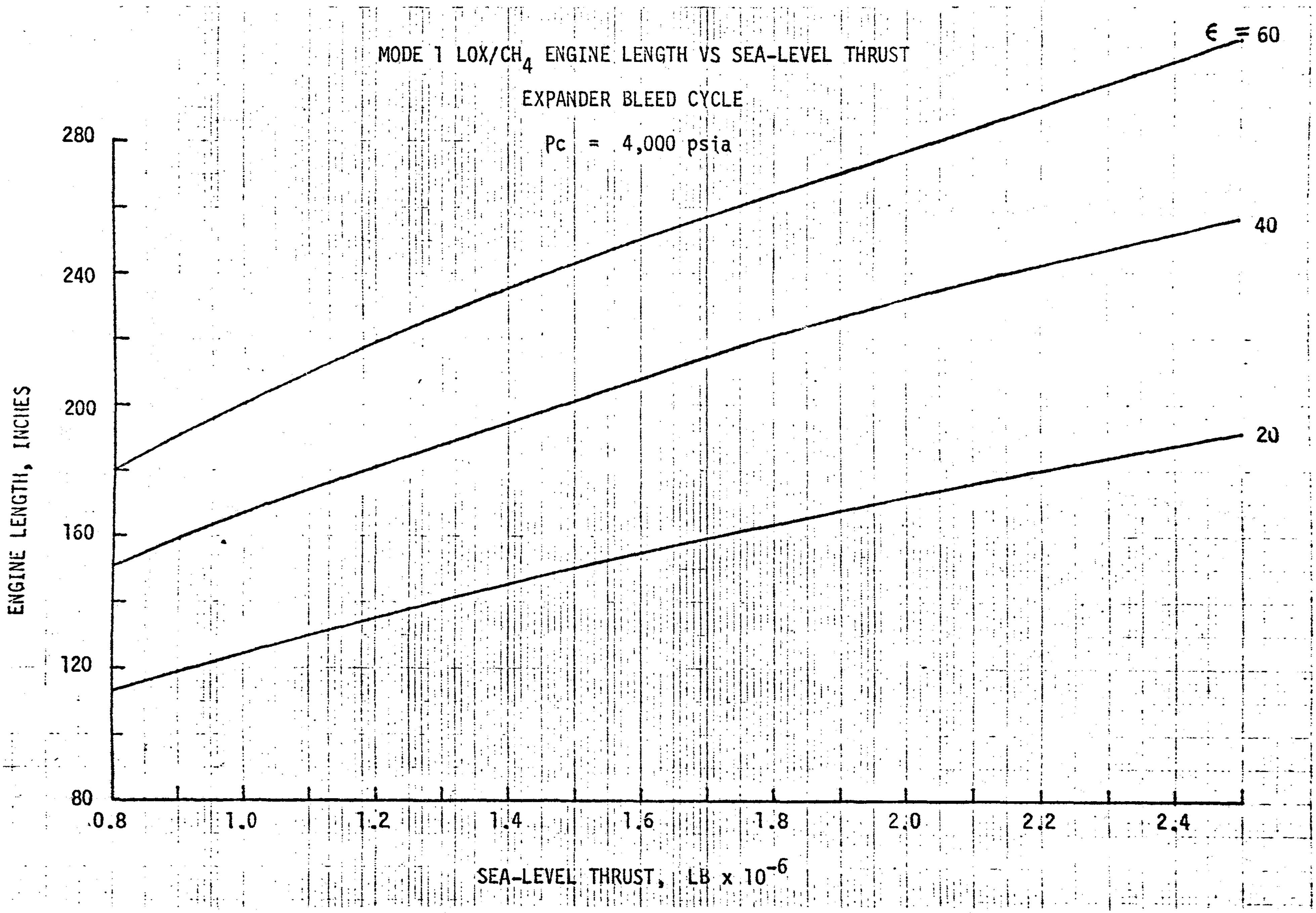


Figure 3-4. Mode I LOX/CH_4 Engine Length vs Sea-Level Thrust, Expander Bleed Cycle

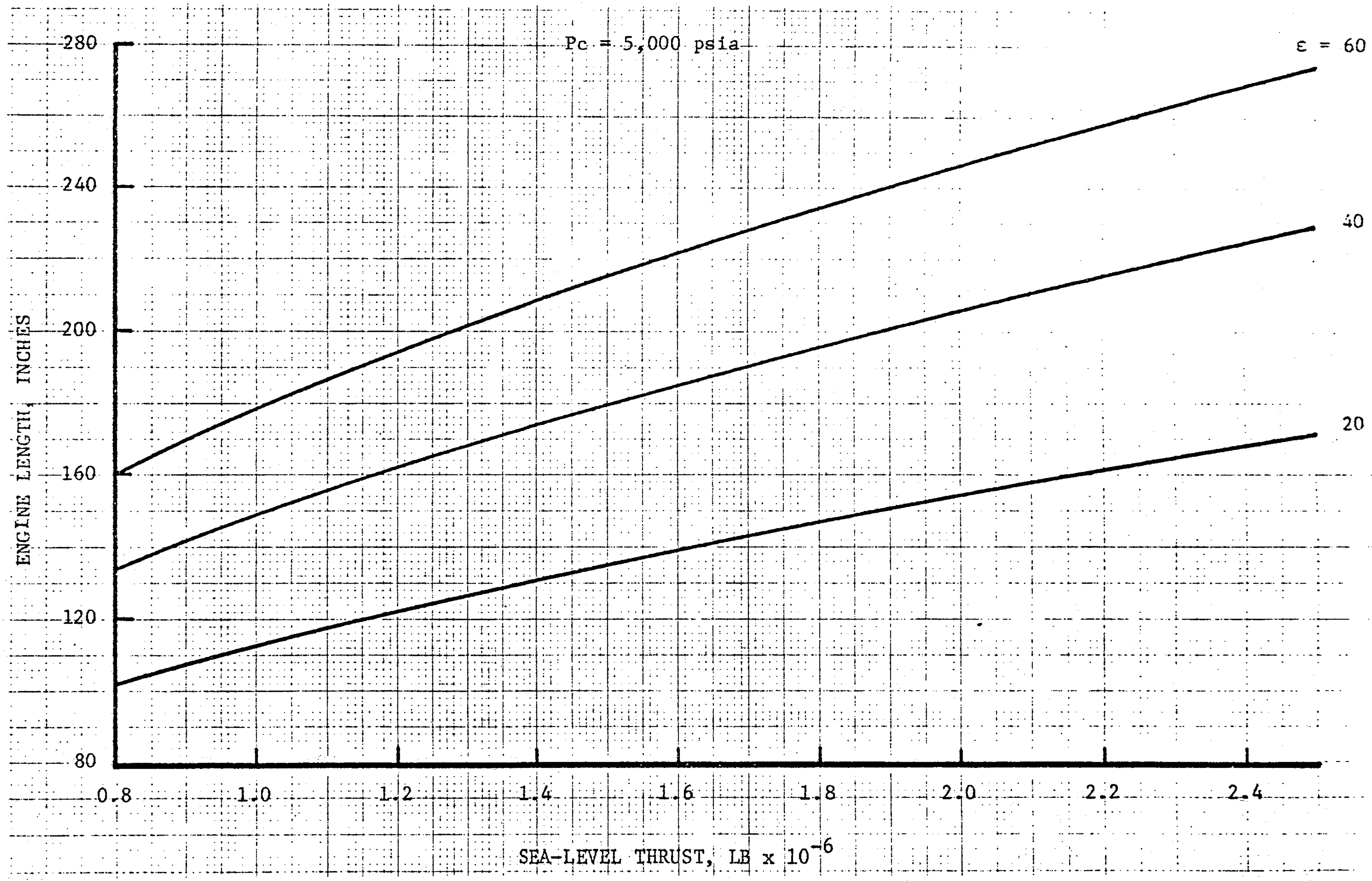


Figure 3-5. Mode I LOX/CH_4 Engine Length vs Sea-Level Thrust, Expander Bleed Cycle

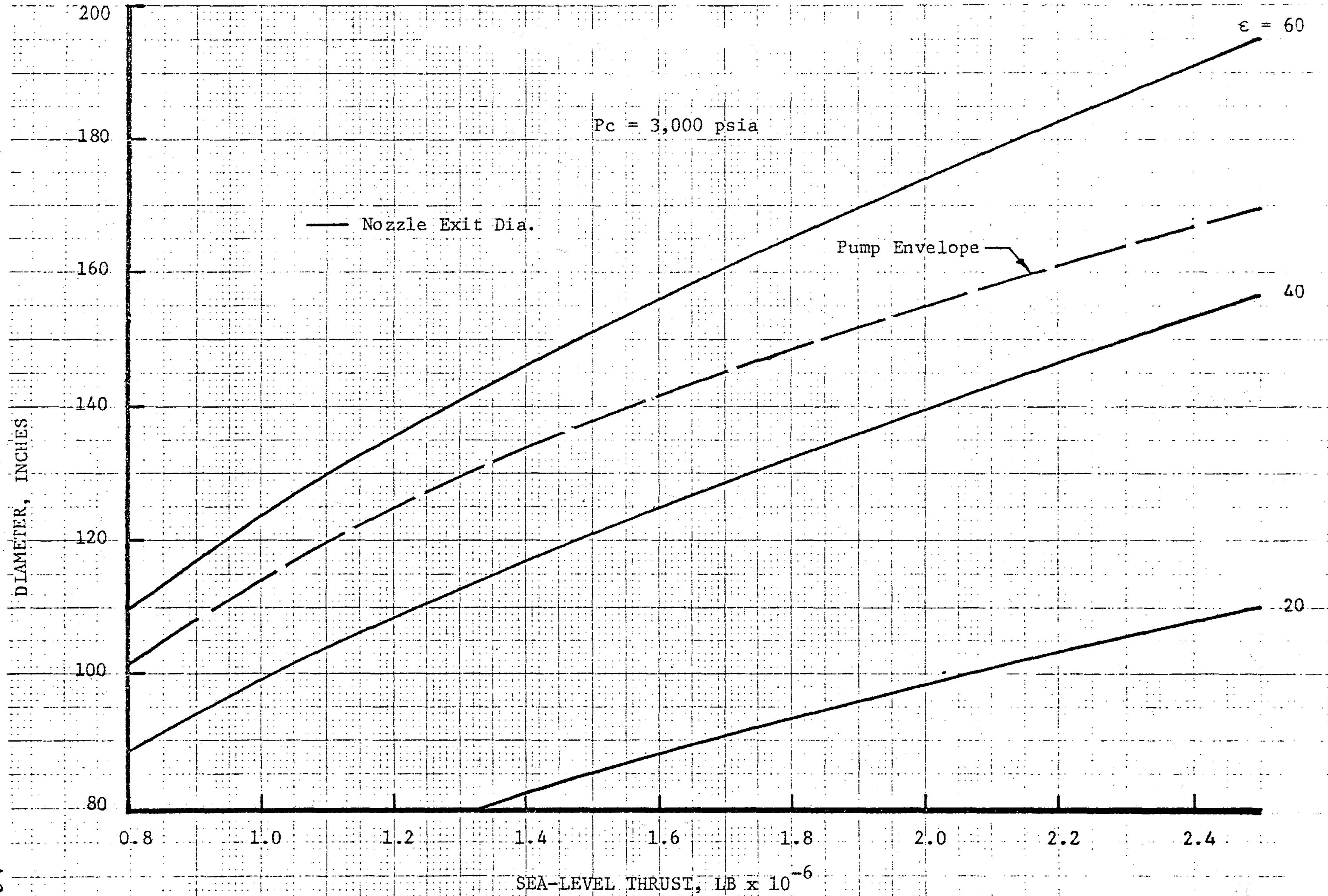


Figure 3-6. Mode I LOX/CH_4 Engine Diameter Parametrics, Expander Bleed Cycle

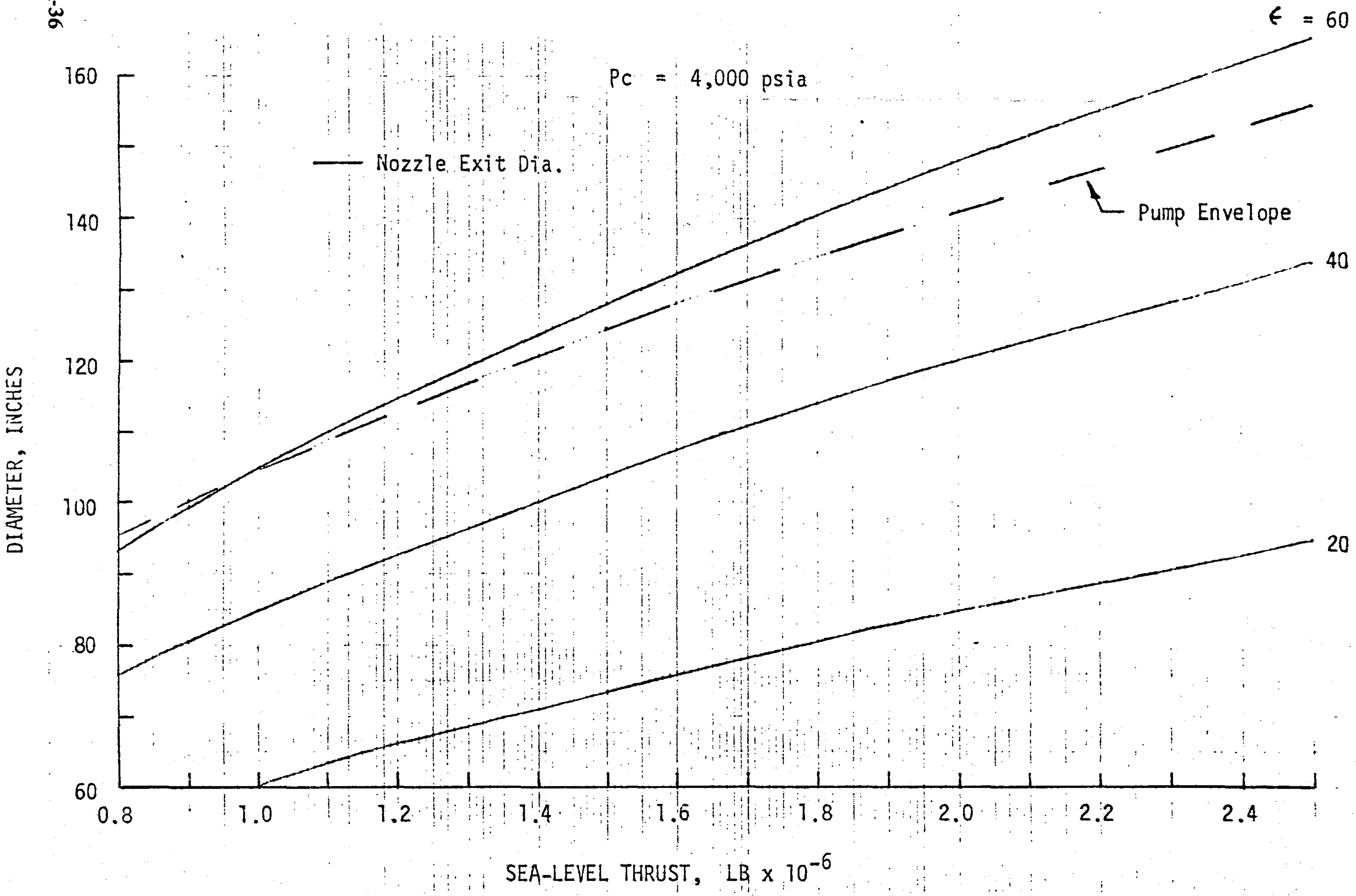


Figure 3-7. Mode I LOX/CH_4 Engine Diameter Parametrics, Expander Bleed Cycle

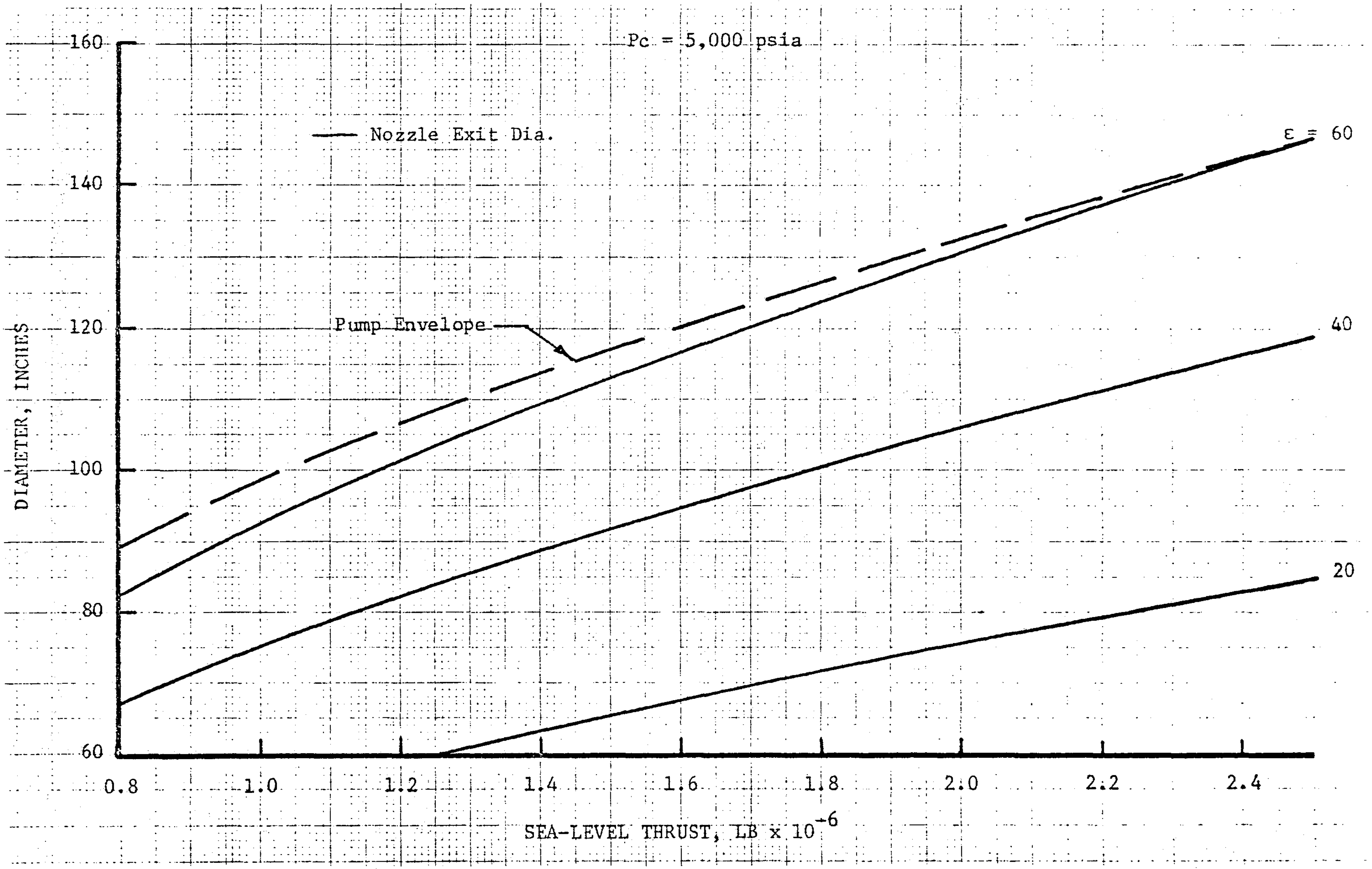


Figure 3-8. Mode I LOX/CH_4 Engine Diameter Parametrics, Expander Bleed Cycle

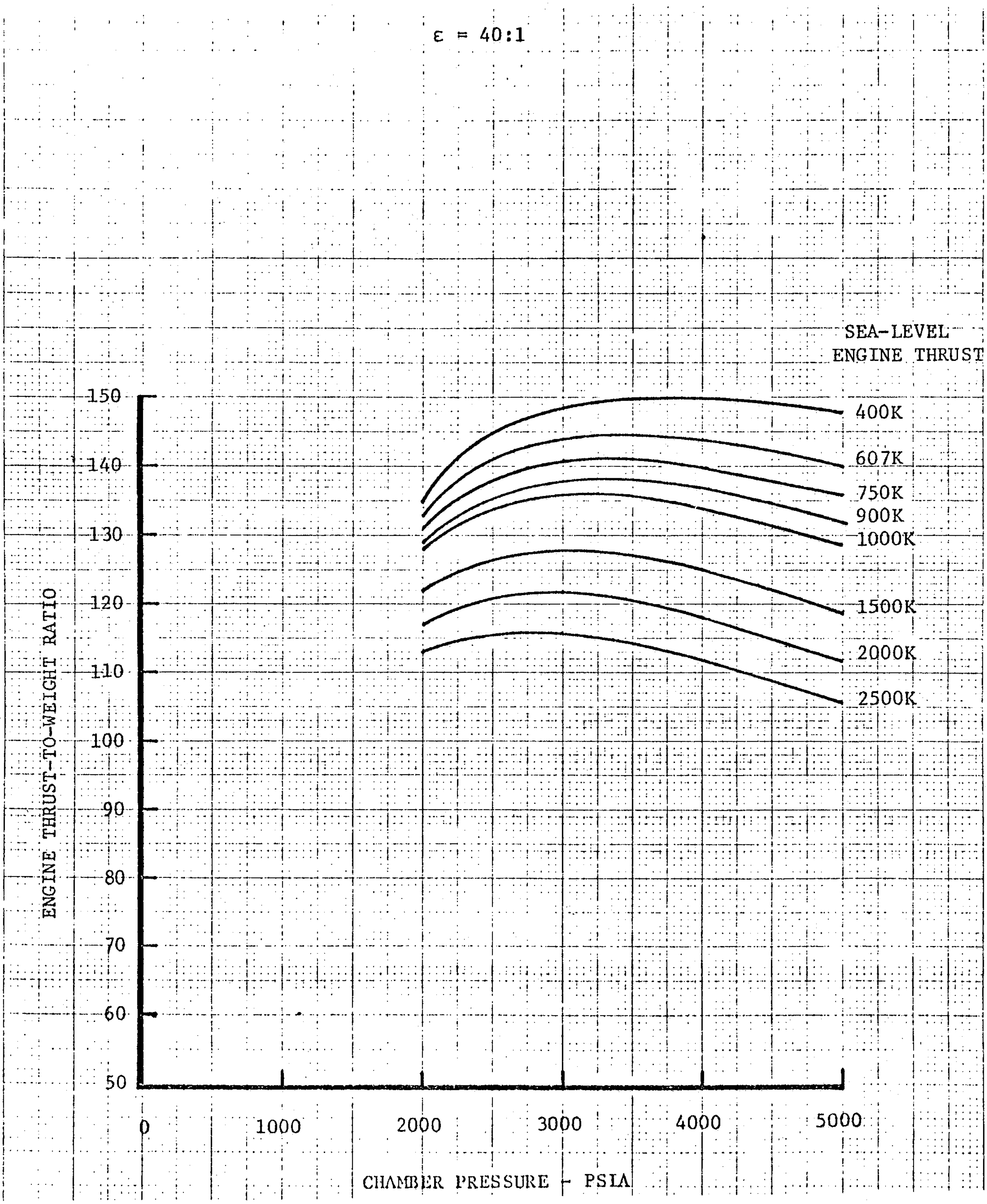


Figure 3-9. Mode I LOX/CH_4 Engine Thrust/Weight Optimization, Expander Bleed Cycle

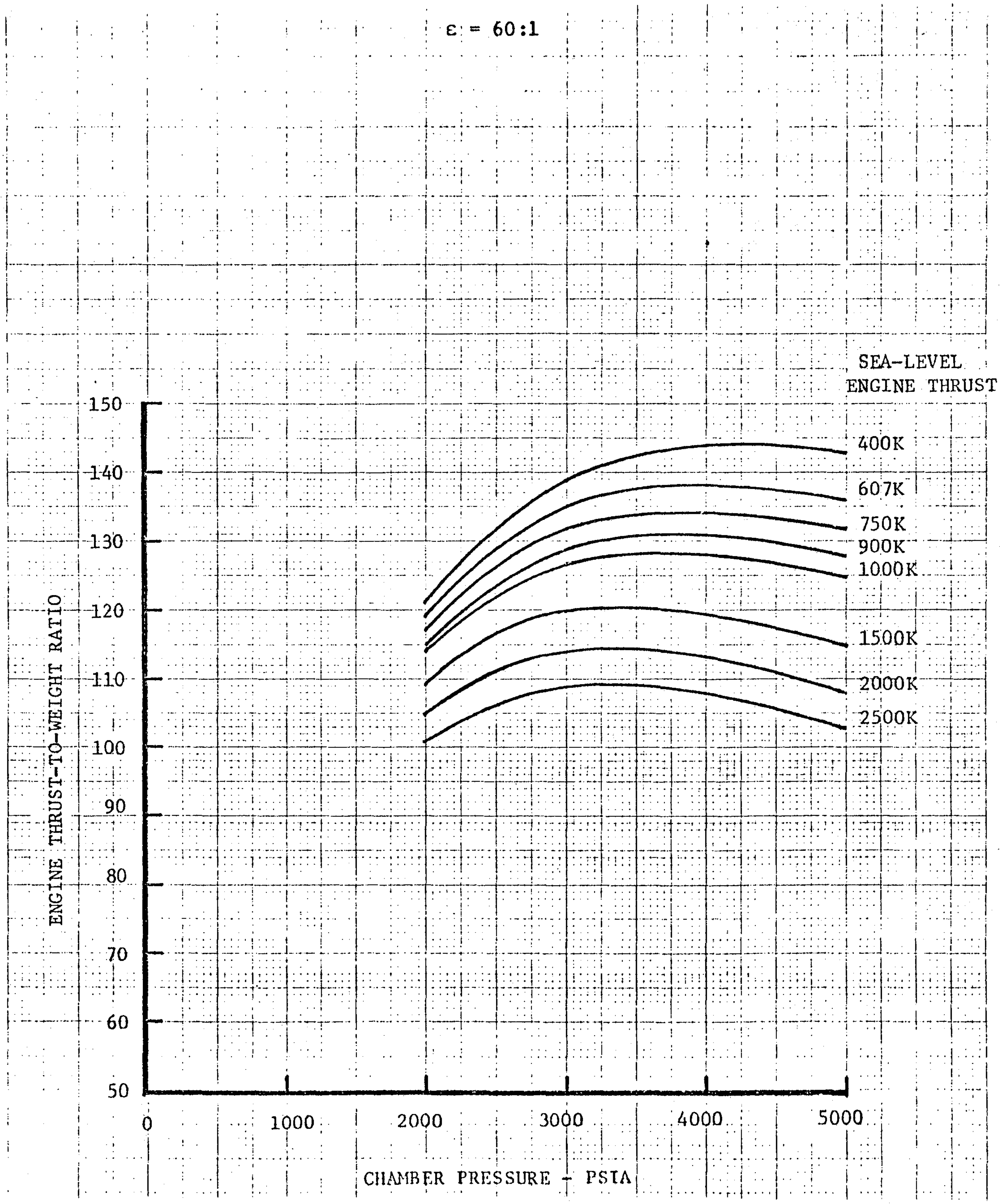


Figure 3-10. Mode I LOX/CH_4 Engine Thrust/Weight Optimization, Expander Bleed Cycle

4.0 ADVANCED TECHNOLOGY FORECAST

This section is the fourth report (see References 1, 2 and 3) submitted in partial fulfillment of the requirements of Contract N-500601-9109, and primarily concerns a propulsion system advanced technology forecast. Included in this section are: (1) Dual Expander (DE) engine parametrics for the thrust range of 600K to 2M-pounds and a thrust split of 60:40 (LOX/CH_4 : LOX/LH_2). ALRC IR&D generated parametric data for LOX/RP-1: LOX/LH_2 engines are also provided to indicate the effect of thrust split on the engine characteristics; (2) Integrated Thruster Assembly (ITA) performance and weight data and drawings; (3) Plug Cluster Engine (PCE) performance data; and (4) propulsion system growth projection and resource requirements for the SSME, a LOX/CH_4 engine, the DE, the Advanced Space Engine (ASE), the ITA, and the PCE.

4.1 DUAL EXPANDER ENGINE PARAMETRIC DATA

4.1.1 LOX/RP-1 and LH_2.

Preliminary design data generated on ALRC IR&D funding are presented for the advanced tripropellant dual-expander engine conceived by R. Beichel. One version of the engine cycle is shown schematically in Figure 4-1. The engine burns oxygen as the oxidizer and RP-1 and hydrogen as the fuels. Some LOX and all of the RP-1 are pumped to high pressure and delivered to a central thrust chamber as liquids where combustion occurs at a chamber pressure of 41,368 kPa (6000 psia). The rest of the LOX and the hydrogen combine in preburners. The gaseous combusion products, both fuel- and oxidizer rich, are delivered to an annular combustion chamber. The engine is ideally suited to mixed mode vehicle applications currently under study by NASA and include the single-stage-to-orbit (SSTO), the heavy lift launch vehicle (HLLV) and the orbiter transfer vehicle (OTV).

The engine performance, weight and envelope parametric data are presented in tables 4-1 through 4-6 and figures 4-2 and 4-3. A thrust chamber pressure of 41,368 kPa (6000 psia) was selected for LOX/RP-1 operation and 20,684 kPa (3000 psia) was selected for the LOX/LH_2 mode. Nozzle area ratios of 70:1 and 50:1 were selected for the LOX/LH_2 and LOX/LH_2 nozzles, respectively. These area ratios result in slight overexpansion at sea-level and high vacuum performance. Trade-off studies by vehicle contractors are required to define the optimum area ratios. It should be noted that for the purposes of the parametric data, all thrust splits were assumed to power balance in the "staged combustion" mode. Therefore, the delivered performance was assumed to be a constant % of the theoretical value.

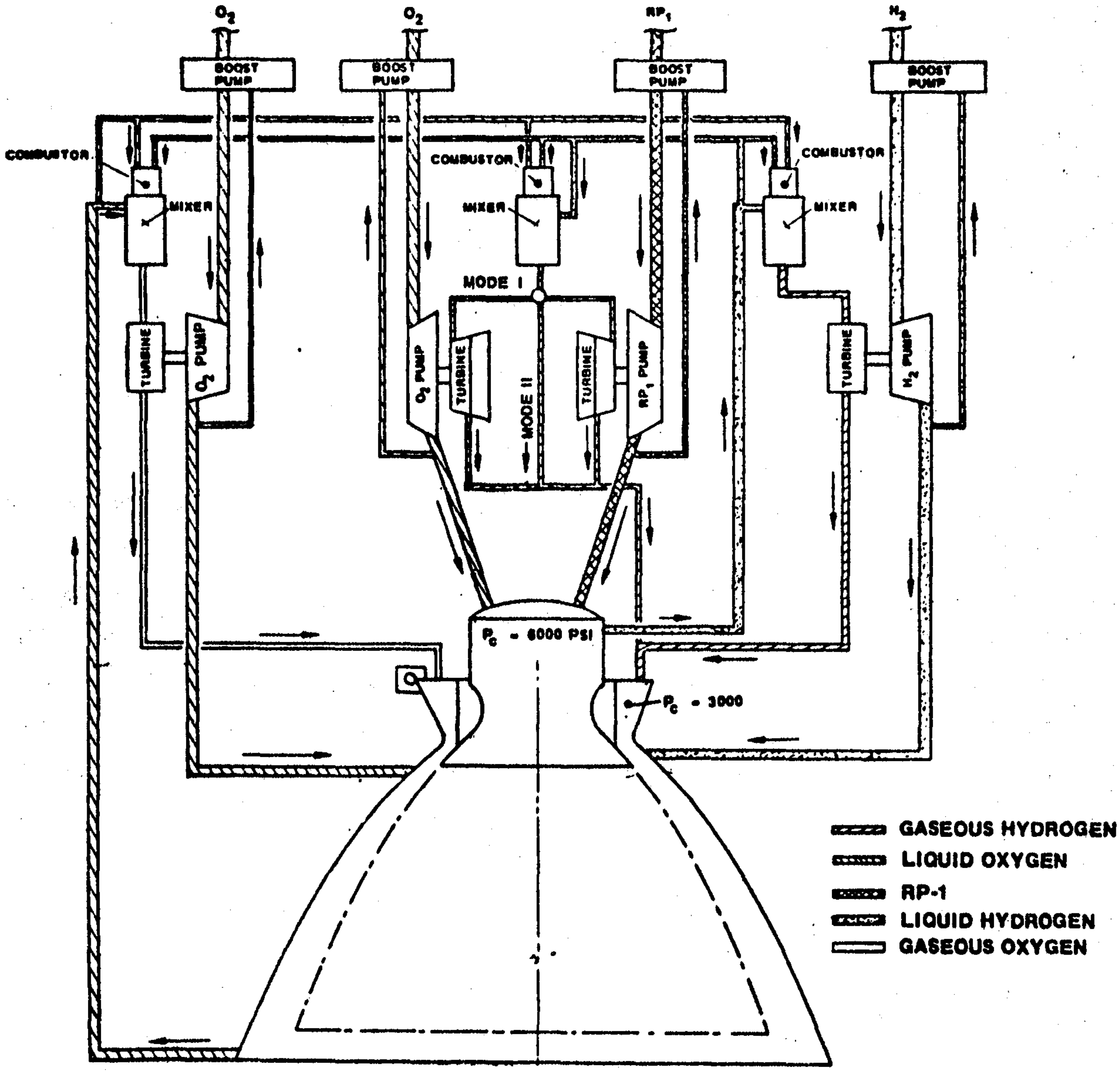


Figure 4-1. Tripropellant Dual-Expander Engine

Table 4-1. Design Point Thrust Split 75/25 Tripropellant Dual-Expander Engine Data Summary

TRIPROPELLANT OPERATION

PROPELLANTS	LOX/RP-1	LOX/LH_2	COMBINED LOX/RP-1 & LH_2
Engine Sea-Level Thrust, lb	456,000	152,000	608,000
Engine Vacuum Thrust, lb	498,800	174,000	672,800
Mixture Ratio	2.9	7.0	3.4
Thrust Chamber Pressure, psia	6,000	3,000	-
Nozzle Area Ratio	70:1	50:1	61.6:1
ODE I_s, Sea-Level, sec	340.6	395.9	-
ODE I_s, Vacuum, sec	372.3	452.2	-
I_s Efficiency, %	97	98	-
I_s, Sea-Level, Delivered, sec	330	387	342.6
I_s, Vacuum, Delivered, sec	361	443	379
Total Flow Rate, lb/sec	1381.8	392.8	1774.6
Fuel Flow Rate, lb/sec	354.3	49.1	403.4
Oxidizer Flow Rate, lb/sec	1027.5	343.7	1371.2

LOX/LH_2 OPERATION ONLY

Engine Vacuum Thrust	181,300
Mixture Ratio	7.0
Thrust Chamber Pressure, psia	3,000
Nozzle Area Ratio	147
ODE I_s, Vacuum, sec	471
I_s Efficiency, %	98
I_s Vacuum, Delivered, sec	461.6
Total Flow Rate, lb/sec	392.8

Table 4-2. Design Point Thrust Split 65/35 Tripropellant Dual-Expander Engine Data Summary

TRIPROPELLANT OPERATION

PROPELLANTS	LOX/RP-1	LOX/LH_2	COMBINED LOX/RP-1 & LH_2
Engine Sea-Level Thrust, lb	395,200	212,800	608,000
Engine Vacuum Thrust, lb	432,300	243,600	675,900
Mixture Ratio	2.9	7.0	3.65
Thrust Chamber Pressure, psia	6,000	3,000	-
Nozzle Area Ratio	70:1	50:1	59.3
ODE I_s, Sea-Level, sec	340.6	395.9	-
ODE I_s, Vacuum, sec	372.3	452.2	-
I_s Efficiency, %	97	98	-
I_s, Sea-Level, Delivered, sec	330	387	347.9
I_s, Vacuum, Delivered, sec	361	443	386.8
Total Flow Rate, lb/sec	1197.6	549.9	1747.5
Fuel Flow Rate, lb/sec	307.1	68.7	375.8
Oxidizer Flow Rate, lb/sec	890.5	481.2	1371.7

LOX/LH_2 OPERATION ONLY

Engine Vacuum Thrust	251,700
Mixture Ratio	7.0
Thrust Chamber Pressure, psia	3,000
Nozzle Area Ratio	110
ODE I_s, Vacuum, sec	467
I_s Efficiency, %	98
I_s Vacuum, Delivered, sec	457.7
Total Flow Rate, lb/sec	549.9

Table 4-3. Design Point Thrust Split 60/40 Tripropellant Dual-Expander Engine Data Summary

TRIPROPELLANT OPERATION

PROPELLANTS	LOX/RP-1	LOX/LH_2	COMBINED LOX/RP-1 & LH_2
Engine Sea-Level Thrust, lb	364,800	243,200	608,000
Engine Vacuum Thrust, lb	399,100	278,400	677,500
Mixture Ratio	2.9	7.0	3.79
Thrust Chamber Pressure, psia	6,000	3,000	-
Nozzle Area Ratio	70:1	50:1	58.2
ODE I_s, Sea-Level, sec	340.6	395.9	-
ODE I_s, Vacuum, sec	372.3	452.2	-
I_s Efficiency, %	97	98	-
I_s, Sea-Level, Delivered, sec	330	387	350.7
I_s, Vacuum, Delivered, sec	361	443	390.7
Total Flow Rate, lb/sec	1105.5	628.4	1733.9
Fuel Flow Rate, lb/sec	283.5	78.6	362.1
Oxidizer Flow Rate, lb/sec	822.0	549.8	1371.8

LOX/LH_2 OPERATION ONLY

Engine Vacuum Thrust	286,400
Mixture Ratio	7.0
Thrust Chamber Pressure, psia	3,000
Nozzle Area Ratio	99
ODE I_s, Vacuum, sec	465
I_s Efficiency, %	98
I_s Vacuum, Delivered, sec	455.7
Total Flow Rate, lb/sec	628.4

Table 4-4. Design Point Thrust Split 50/50 Tripropellant Dual-Expander Engine Data Summary

TRIPROPELLANT OPERATION

PROPELLANTS	LOX/RP-1	LOX/LH_2	COMBINED LOX/RP-1 & LH_2
Engine Sea-Level Thrust, lb	304,000	304,000	608,000
Engine Vacuum Thrust, lb	332,500	348,000	680,500
Mixture Ratio	2.9	7.0	4.1
Thrust Chamber Pressure, psia	6,000	3,000	-
Nozzle Area Ratio	70:1	50:1	56.3
ODE I_s, Sea-Level, sec	340.6	395.9	-
ODE I_s, Vacuum, sec	372.3	452.2	-
I_s Efficiency, %	97	98	-
I_s, Sea-Level, Delivered, sec	330	387	356.3
I_s, Vacuum, Delivered, sec	361	443	398.7
Total Flow Rate, lb/sec	921.1	785.5	1706.6
Fuel Flow Rate, lb/sec	236.2	98.2	334.4
Oxidizer Flow Rate, lb/sec	684.9	687.3	1372.2

LOX/LH_2 OPERATION ONLY

Engine Vacuum Thrust	356,100
Mixture Ratio	7.0
Thrust Chamber Pressure, psia	3,000
Nozzle Area Ratio	82.5
ODE I_s, Vacuum, sec	462.5
I_s Efficiency, %	98
I_s Vacuum, Delivered, sec	453.3
Total Flow Rate, lb/sec	785.5

Table 4-5. Design Point Thrust Split 30/70 Tripropellant Dual-Expander Engine Data Summary

TRIPROPELLANT OPERATION

PROPELLANTS	LOX/RP-1	LOX/LH_2	COMBINED LOX/RP-1 & LH_2
Engine Sea-Level Thrust, lb	182,400	425,600	608,000
Engine Vacuum Thrust, lb	199,500	487,200	686,700
Mixture Ratio	2.9	7.0	4.92
Thrust Chamber Pressure, psia	6,000	3,000	-
Nozzle Area Ratio	70:1	50:1	53.3
ODE I_s, Sea-Level, sec	340.6	395.9	-
ODE I_s, Vacuum, sec	372.3	452.2	-
I_s Efficiency, %	97	98	-
I_s, Sea-Level, Delivered, sec	330	387	367.9
I_s, Vacuum, Delivered, sec	361	443	415.6
Total Flow Rate, lb/sec	552.7	1099.7	1652.4
Fuel Flow Rate, lb/sec	141.7	137.5	279.2
Oxidizer Flow Rate, lb/sec	411.0	962.2	1373.2

LOX/LH_2 OPERATION ONLY

Engine Vacuum Thrust	492,800
Mixture Ratio	7.0
Thrust Chamber Pressure, psia	3,000
Nozzle Area Ratio	63.9
ODE I_s, Vacuum, sec	457.2
I_s Efficiency, %	98
I_s Vacuum, Delivered, sec	448.1
Total Flow Rate, lb/sec	1099.7

Table 4-6. Dual Expander Engine Preliminary Weights

	WEIGHT, LB	WEIGHT, LB	WEIGHT, LB	WEIGHT, LB
Seal Level Thrust Split, % LOX/RP-1/% LOX/LH_2	75/25	65/35	50/50	30/70
COMPONENT				
Gimbal	218	219	222	225
Injector (LOX/RP-1)	496	430	331	198
Combustion Chamber (LOX/RP-1)	220	201	170	125
Injector and Combustion Chamber (LOX/LH_2)	441	545	700	907
Nozzle	294	280	254	205
Preburners (3)	79	95	119	150
Fuel Valves and Actuation	161	166	174	184
Oxidizer Valves and Actuation	193	193	193	193
Two (2) Low Speed LOX TPA's	300	300	300	300
Low Speed RP-1 TPA	41	34	24	12
Low Speed LH_2 TPA	27	42	69	108
Two (2) High Speed LOX TPA's	602	602	602	602
High Speed RP-1 TPA	159	131	92	46
High Speed LH_2 TPA	250	393	637	1004
Low Pressure Lines	177	182	188	194
High Pressure Lines	283	306	358	454
Ignition System	100	100	100	100
Miscellaneous	442	442	442	442
TOTAL DRY WEIGHT	4483	4661	4975	5449
Estimated Engine Weight 1990 Technology*	3362	3496	3731	4087

*25% Decrease

NOTES: (1) TOTAL SEA-LEVEL THRUST = 608,000 LB
(2) LOX/RP-1 NOZZLE ε = 70:1
(3) LOX/LH_2 NOZZLE ε = 50:1
(4) LOX/RP-1 P_c = 6000 PSIA
(5) LOX/LH_2 P_c = 3000 PSIA

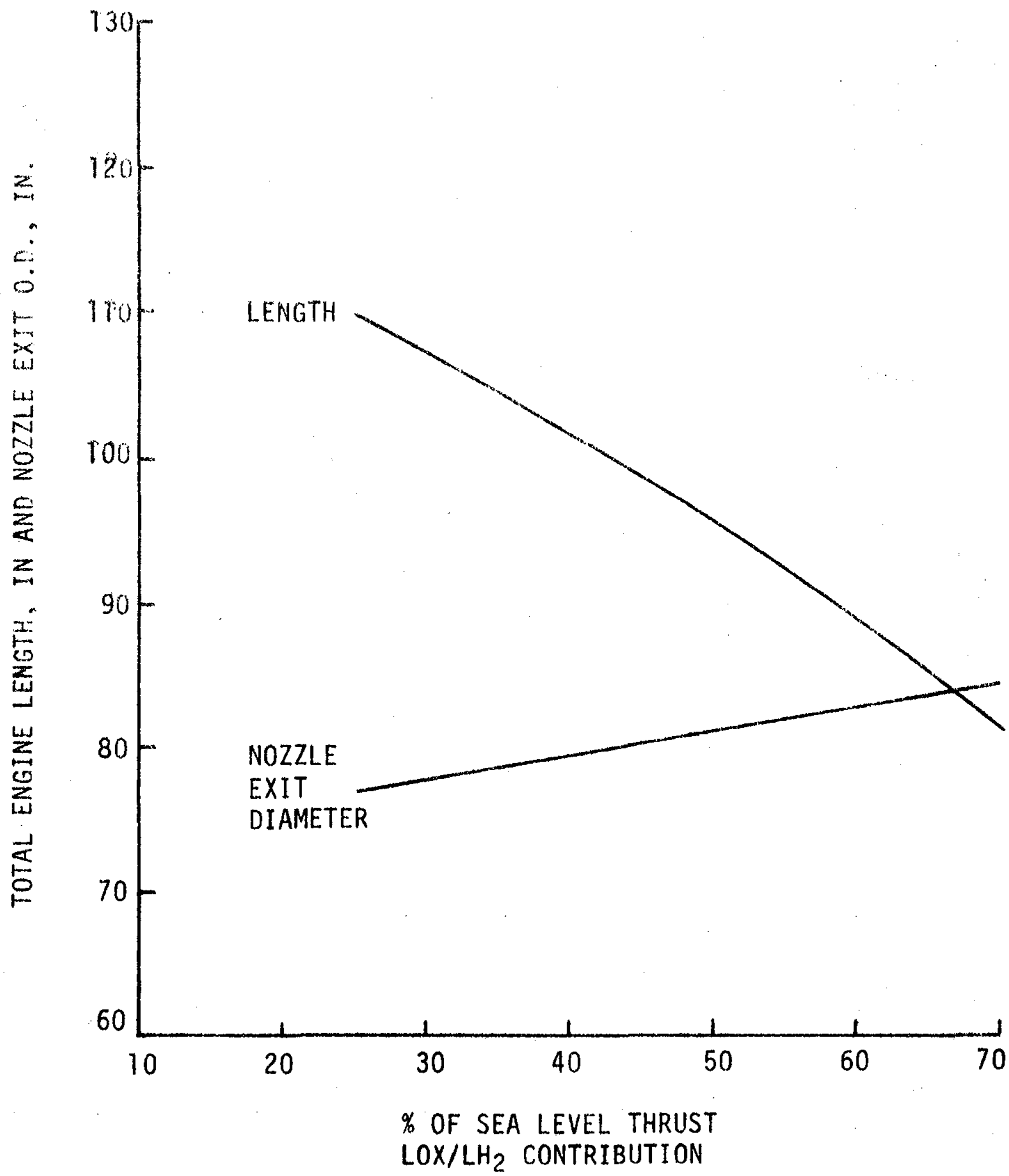


Figure 4-2. Dual-Expander Tripropellant Engine Envelope Parametrics

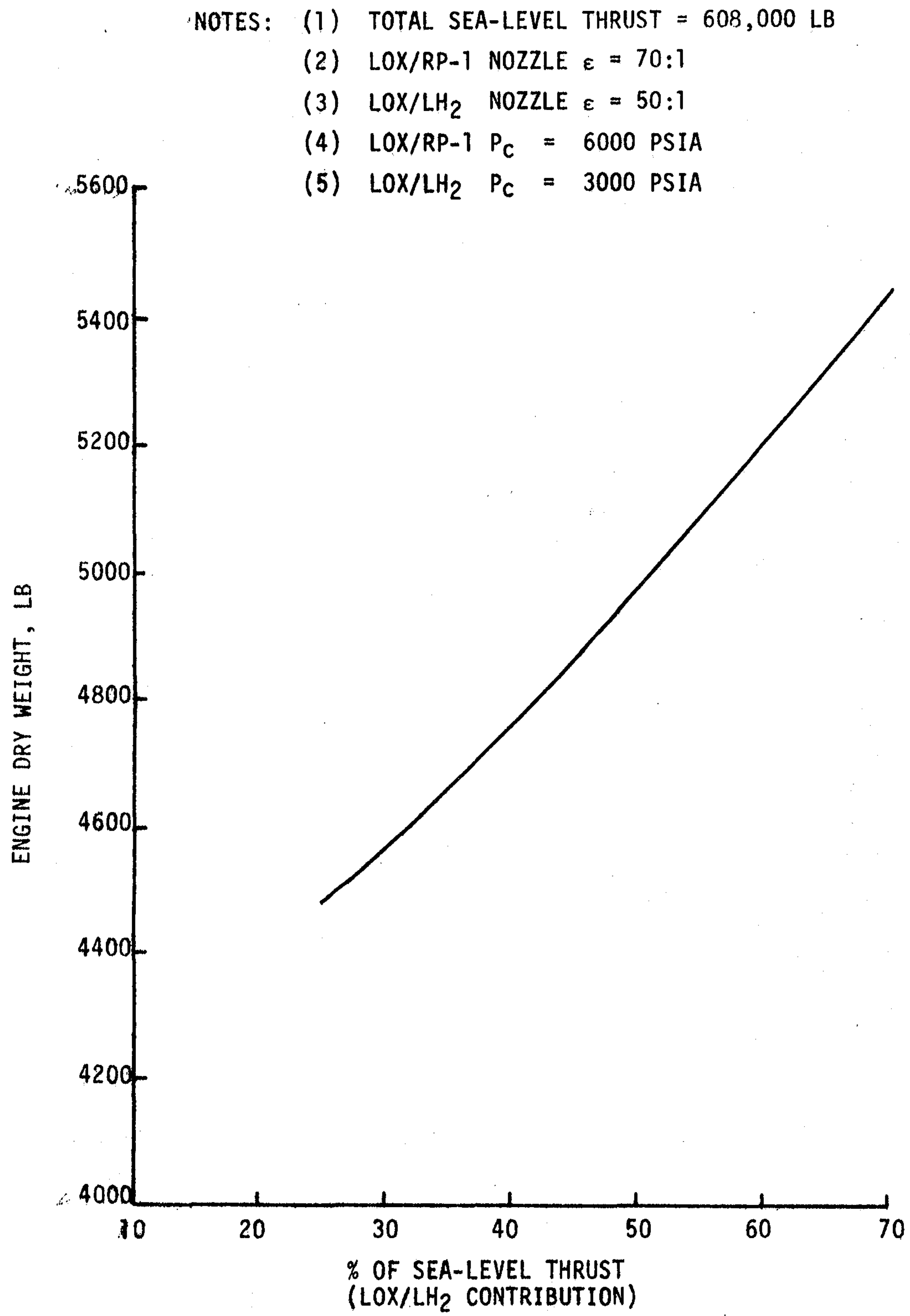


Figure 4-3. Dual-Expander Tripropellant Engine Weight Parametrics

Table 4-7. Tripropellant Dual-Expander Engine Preliminary Operating Specifications Design Point Thrust Split: 60% LOX/RP-1, 40% LOX/LH_2

ENGINE	LOX/RP-1	LOX/LH_2	COMBINED LOX/RP-1 & LH_2
Sea-Level Thrust, lb.	364,800	243,200	608,000
Vacuum Thrust, lb.	399,100	278,400	677,500
Sea-Level Specific Impulse, sec.	330	387	350.7
Vacuum Specific Impulse, sec.	361	443	390.7
Total Flow Rate, lb/sec.	1105.5	628.4	1733.9
Mixture Ratio	2.9	7.0	3.79
Oxidizer Flow Rate, lb/sec.	822.0	549.8	1371.8
Fuel Flow Rate, lb/sec.	283.5	78.6	362.1

THRUST CHAMBER	LOX/RP-1	LOX/LH_2	COMBINED LOX/RP-1 & LH_2
Sea-Level Thrust, lb.	364,800	243,200	608,000
Vacuum Thrust, lb.	399,100	278,400	677,500
Sea-Level Specific Impulse, sec.	330	387	350.7
Vacuum Specific Impulse, sec.	361	443	390.7
Chamber Pressure, psia	6,000	3,000	-
Nozzle Area Ratio	70	50	58.2
Mixture Ratio	2.9	7.0	3.79
Throat Area, $in.^2$	33.3	47.9	81.2
Nozzle Exit Area, $in.^2$	2,334	2,395	4,729
Injector Oxygen Flow Rate, lb/sec.	822.0	-	822.0
Injector RP-1 Flow Rate, lb/sec.	283.5	-	283.5
Injector Ox.-Rich Gas Flow Rate, lb/sec.	-	500.17	500.17
Injector Fuel-Rich Gas Flow Rate, lb/sec.	-	128.23	128.23

Table 4-7. (Continued)

PREBURNERS (LOX & LH_2 DRIVE FLOWS)	LOX/LH_2 OX.-RICH	LOX/LH_2 FUEL-RICH
Chamber Pressure, psia	4,572	6,026
Combustion Temperature, °R	1,660	1,850
Hydrogen Inlet Temperature, °R	540	540
Oxygen Inlet Temperature, °R	400	400
Mixture Ratio	110	0.73
Oxidizer Flow Rate, lb/sec.	495.66	27.93
Fuel Flow Rate, lb/sec.	4.51	38.27

TURBINES	LOX PUMP	LH_2 PUMP
Inlet Pressure, psia	4,572	6,026
Inlet Temperature, °R	1,660	1,850
Total Gas Flow Rate, lb/sec.	500.17	66.20
Gas Properties		
C_p, Specific Heat @ Constant Pressure, Btu/lb.°R	0.277	2.17
γ, Ratio of Specific Heats	1.312	1.358
Shaft Horsepower	20,450	45,950
Efficiency, %	80	81
Speed, rpm	21,900	55,500
Pressure Ratio (Total to Static)	1.411	1.86

MAIN PUMPS	LOX	LH_2
Total Outlet Flow Rate, lb/sec.	549.8	78.6
Volumetric Flow Rate, gpm	3,480	8,020
NPSH, ft.	294	1,700
Suction Specific Speed, (rpm) $(gpm)^{1/2}/(ft.)^{3/4}$	18,200	18,800
Discharge Pressure, psia	8,200	8,000
Number of Stages	2	3
Specific Speec, (rpm) $(gpm)^{1/2}/(ft.)^{3/4}$	1,500	1,000
Total Head Rise, ft.	16,360	254,340
Efficiency, %	82	80

PREBURNER (LOX & LH_2 DRIVE FLOW)		
Chamber Pressure, psia	6,026	
Combustion Temperature, °R	1,850	
Hydrogen Inlet Temperature, °R	540	
Oxygen Inlet Temperature, °R	400	
Mixture Ratio	0.73	
LOX Flow Rate, lb/sec.	26.21	
Hydrogen Flow Rate, lb/sec.	35.82	
Total Flow Rate, lb/sec.	62.03	

TURBINES	LOX PUMP	RP-1 PUMP
Inlet Pressure, psia	6,026	6,026
Inlet Temperature, °R	1,850	1,850
Total Gas Flow Rate, lb/sec.	41.58	20.45
Gas Properties		
C_p, Specific Heat @ Constant Pressure, Btu/lb. °R	2.17	2.17
γ , Ratio of Specific Heats	1.358	1.358
Shaft Horsepower	25,800	12,690
Efficiency, %	72	72
Speed, rpm	15,750	29,400
Pressure Ratio (Total to Static)	1.86	1.86

MAIN PUMPS		
Total Outlet Flow Rate, lb/sec.	822.0	283.5
Volumetric Flow Rate, gpm	5,200	2,550
NPSH, ft.	294	364
Suction Specific Speed, (rpm) $(gpm)^{1/2}/(ft.)^{3/4}$	16,000	17,800
Discharge Pressure, psia	6,950	6,950
Number of Stages	2	2
Specific Speed, (rpm) $(gpm)^{1/2}/(ft.)^{3/4}$	1,500	1,500
Total Head Rise, ft.	13,800	19,700
Efficiency, %	82	82

Preliminary vehicle study results appear to favor an engine with a 60% LOX/RP-1 and 40% LOX/LH_2 thrust split. Preliminary performance data for this engine is shown in table 4-3. For a LOX/LH_2 system chamber pressure of 20,684 kPa (3000 psia) and the cycle shown in figure 4-1, pump discharge pressures of 56,537 kPa (8200 psia) and 55,158 kPa (8000 psia) are required for the LOX and LH_2 pumps respectively. Preliminary specifications for this design point are shown in table 4-7 and a pressure schedule is presented in table 4-8. This oxidizer-rich preburner side on this cycle has excess pressure drop as noted by the high control ΔP. This suggests that the cycle should be modified to make use of the excess power available.

4.1.2 LOX/CH_4 and LH_2.

Preliminary operating specifications for a LOX/methane and LOX/LH_2 dual expander engine are given in table 4-9. Weight and envelope parametric data for this engine are presented in table 4-10 and figures 4-4 and 4-5.

4.2 INTEGRATED THRUSTER ASSEMBLY DATA

The Integrated Thruster Assembly (ITA), figures 4-6 and 4-7 is a flightweight GH_2/GO_2 ACPS engine employing a spark initiated igniter. The nominal operating conditions are: 672 N (1500 lbf) thrust, 207 N/cm^2 (300 psia) chamber pressure, and a 4.0 mixture ratio, as given in table 4-11. The thruster has demonstrated a steady state specific impulse of 435 sec, and a 27 kg-sec bit impulse performance of 368 sec. The ITA consists of a premix triplet injector, a regeneratively cooled chamber, and a dump-film cooled throat and skirt; an ox rich torch type igniter and integral exciter/spark plug; two igniter valves, and two main propellant valves. The ITA S/N 002 was fired 42,266 times over 4200 full thermal cycles. A similar unit achieved 51,000 cycles in life testing at NASA/LeRC.

The results of the ITA development program are as follows: (1) the ITA design is satisfactory, simple to operate, and has adequate life, (2) the igniter is very reliable, (3) chamber coolant part to part hydraulic characteristics have no significant variations, (4) 51,000 pulses were demonstrated on a single unit, (5) the main propellant valves were unsatisfactory, (6) some fabrication problems were encountered, (7) operation of the ITA is excellent, (8) the predicted thermal cycle life of 65,000 cycles agrees with measured temperature data, (9) fuel lead starts can result in damage, thus .01 to .02 sec oxidizer leads are used, (10) fuel lag shutdowns are preferred, (11) pulse performance is optimized with a .006 oxidizer lead, (12) the specified minimum impulse bit (MIB) performance of 222 N-sec (50 lbf-sec) was not achieved, the best was 267 N-sec (60 lbf-sec), (13) the

Table 4-8. Dual-Expander Engine, Preliminary Pressure Schedule (PSI)
60% LOX/RP-1 and 40% LOX/LH_2 Thrust Split

Component	LOX/RP-1 Thrust Chamber		Fuel-Rich LOX/LH_2 Gas Generator		Ox-Rich LOX/LH_2 Preburner		Fuel-Rich LOX/LH_2 Preburner	
PRESSURE, psia / Propellant	LOX	RP-1	LOX	LH_2	LOX	LH_2	LOX	LH_2
Main Pump Discharge	6,950	6,950	8,200	8,000	8,200	8,000	8,200	8,000
Main Shutoff Valve Inlet	6,950	6,950	8,200	8,000	8,200	8,000	8,200	8,000
ΔP Shutoff Valve	70	70	82	80	82	80	82	80
Valve Outlet	6,880	6,880	8,118	7,920	8,118	7,920	8,118	7,920
ΔP Line	40	40	40	40	40	40	40	40
Coolant Jacket Inlet	-	-	8,078	7,880	8,078	7,880	8,078	7,880
ΔP Coolant Jacket	-	-	952	1,070	952	1,070	952	1,070
Coolant Jacket Outlet	-	-	7,126	6,810	7,126	6,810	7,126	6,810
ΔP Line	-	-	40	40	40	40	40	40
Preburner (G.G.) Control Inlet	-	-	7,086	6,770	7,086	6,770	7,086	6,770
ΔP Control	-	-	337	322	1,965	1,878	337	322
Preburner (G.G.) Inlet	-	-	6,749	6,448	5,121	4,892	6,749	6,448
ΔP Preburner	-	-	723	422	549	320	723	422
Turbine Inlet	-	-	6,026		4,572		6,026	
ΔP Turbine (Total to Static)	-	-	2,786		1,332		2,786	
Turbine Exit Pressure Static	-	-	3,240		3,240		3,240	
Main Injector Inlet, Total	6,840	6,840	3,240		3,240		3,240	
ΔP Injector	840	840	240		240		240	
Chamber Pressure, Plenum	6,000		3,000		3,000		3,000	

Table 4-9. Tripropellant Dual-Expander Engine Preliminary Operating Specifications Design Point Thrust Split: 60% LOX/CH_4, 40% LOX/LH_2

ENGINE	STREAM TUBES LOX/CH_4	STREAM TUBES LOX/LH_2	MODE I COMBINED LOX/CH_4 & LH_2	MODE II LOX/LH_2
Sea-Level Thrust, lb.	364,800	243,200	608,000	-
Vacuum Thrust, lb	398,900	278,400	677,300	286,500
Sea-Level Specific Impulse, sec.	339.1	387	356.8	-
Vacuum Specific Impulse, sec.	370.8	443	397.4	456
Total Flow Rate, lb/sec.	1075.79	628.4	1704.2	628.4
Mixture Ratio	3.6	7.0	4.45	7.0
Oxidizer Flow Rate, lb/sec.	841.92	549.8	1391.7	549.8
Fuel Flow Rate, lb/sec.	233.87	78.6	312.5	78.6
THRUST CHAMBER				
Sea-Level Thrust, lb.	364,800	243,200	608,000	-
Vacuum Thrust, lb.	398,900	278,400	677,300	286,500
Sea-Level Specific Impulse, sec.	339.1	387	356.8	-
Vacuum Specific Impulse, sec.	370.8	443	397.4	456
Chamber Pressure, psia	6,000	3,000	-	3,000
Nozzle Area Ratio	70	50	58.3	100
Mixture Ratio	3.6	7.0	4.45	7.0
Throat Area, $in.^2$	34.01	47.9	81.9	47.9
Nozzle Exit Area, $in.^2$	2,381	2,395	4,776	4,776
Injector Oxygen Flow Rate, lb/sec.	841.92	-	841.92	-
Injector CH_4 Flow Rate, lb/sec.	233.87	-	233.87	-
Injector Ox.-Rich Gas Flow Rate,lb/sec	-	500.17	500.17	500.17
Injector Fuel-Rich Gas Flow Rate,lb/sec	-	128.23	128.23	128.23

Table 4-10. Estimation of $LO_2/LH_2 + CH_4$ Dual Expander Stage Combustion Engine Component Weights

COMPONENT	60/40 $(LOX/CH_4)/(LOX/CH_2)$ STAGED COMBUSTION
Gimbal	220
Injector (LOX/HDF)	397
Combustion Chamber (LOX/HDF)	192
Injector & Combustion Chamber (LOX/LH_2)	589
Nozzle	274
Preburners (3)	103
Fuel Valves and Actuation	180
Oxidizer Valves & Actuation	194
Two Low Speed LOX TPA's	305
Low Speed HDF TPA	37
Low Speed LH_2 TPA	52
Two High Speed LOX TPA's	611
High Speed HDF TPA	190
High Speed LH_2 TPA	475
Low Pressure Lines	198
High Pressure Lines	346
Ignition System	100
Miscellaneous	442
Total Dry Weight	4905
Vacuum Thrust/Weight	138
Vacuum Thrust (lb)	677,300
Sea Level Thrust/Weight	124
Sea Level Thrust (lb)	608,000
Chamber Pressure (psia)	6000/3000
Mixture Ratio	4.45
LO_2 Flow Rate (lb/s)	1391.7
CH_4 Flow Rate (lb/s)	233.9
LH_2 Flow Rate (lb/s)	78.6
Length (in)	110.5
Exit Dia. (in)	78.0

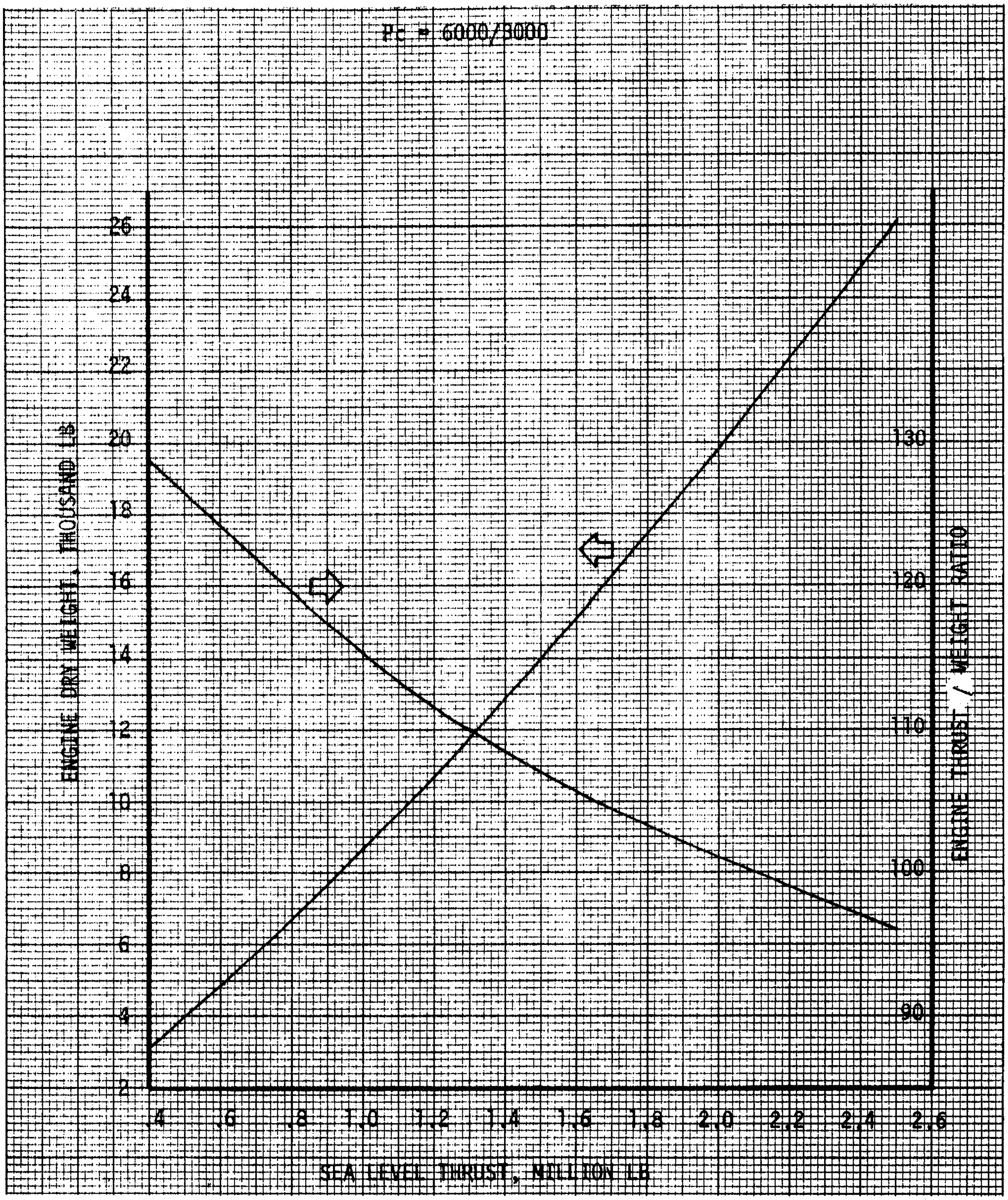


Figure 4-4. Dual Expander Engine Weight Parametrics – 60% LOX/CH_4 – 40% LOX/LH_2

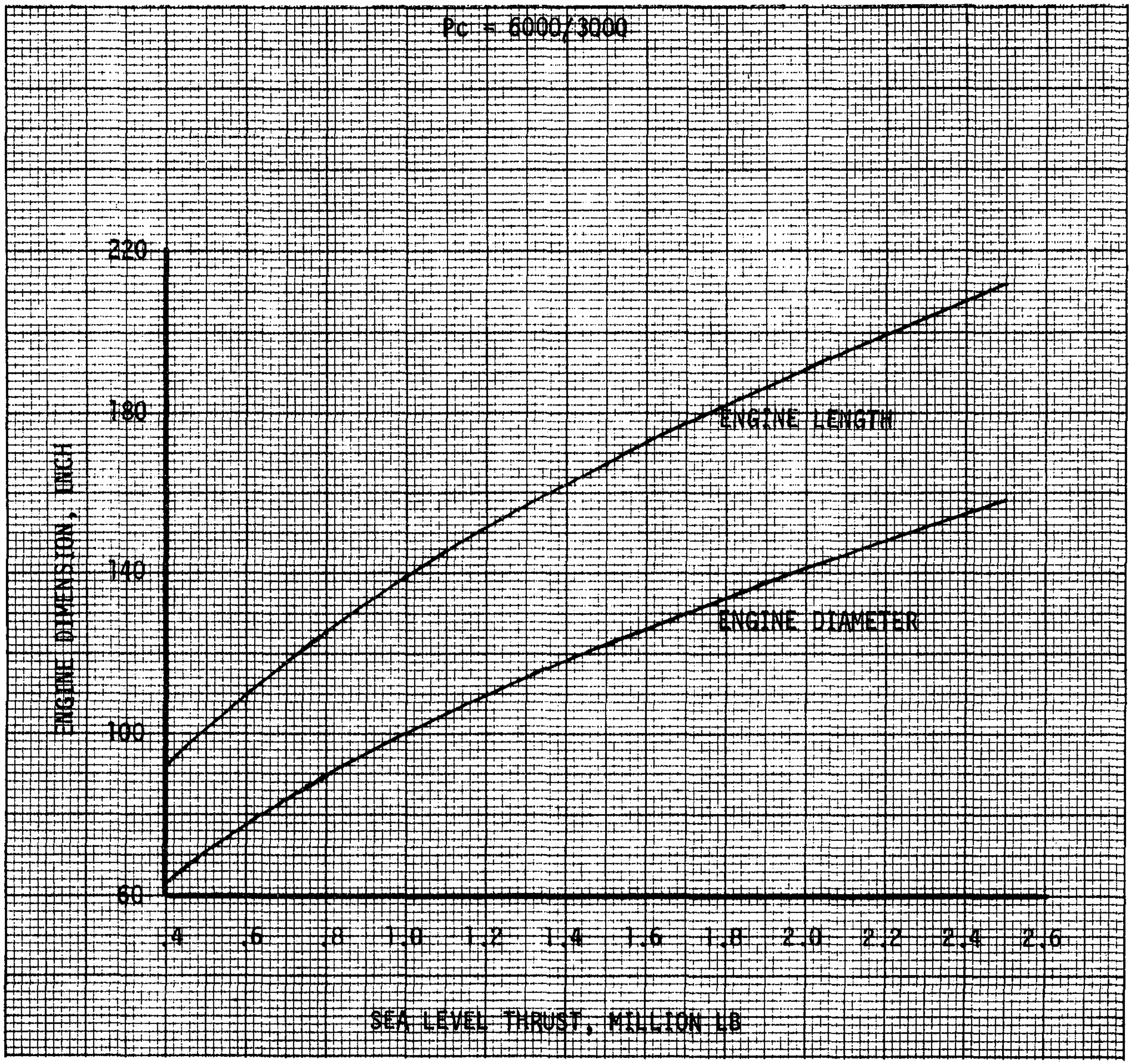


Figure 4-5. Dual Expander Engine Envelope Parametrics – 60% LOX/CH_4 – 40% LOX/LH_2

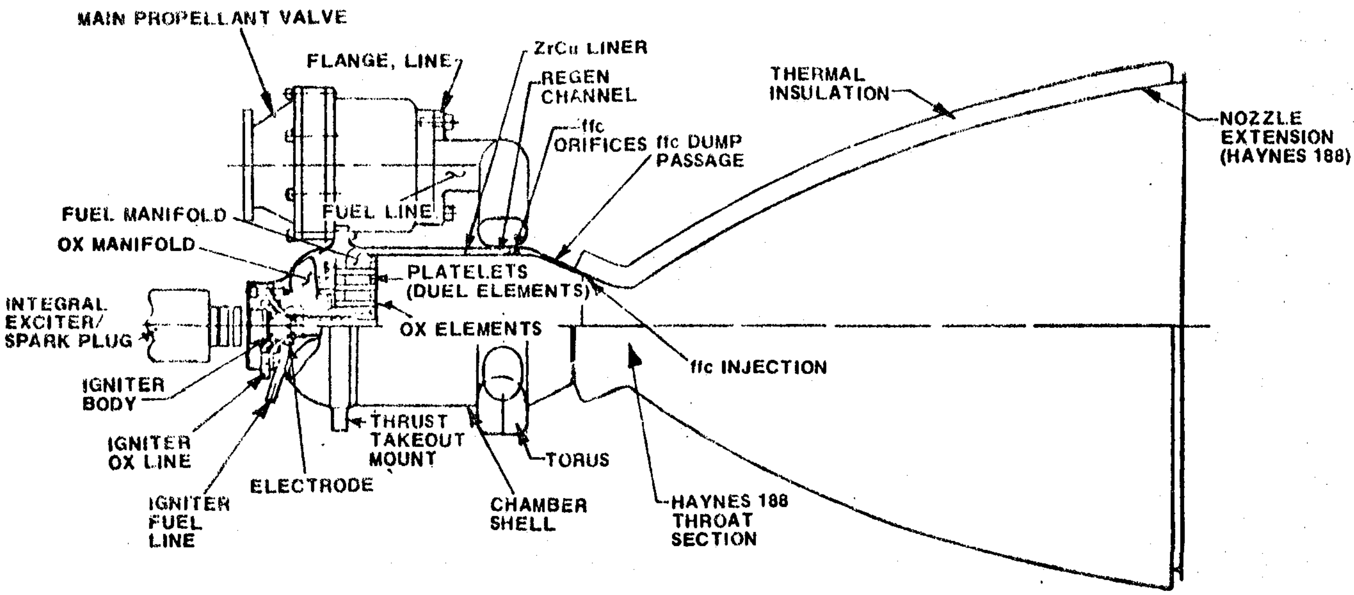


Figure 4-6. ITA is a Flightweight High Technology Thruster

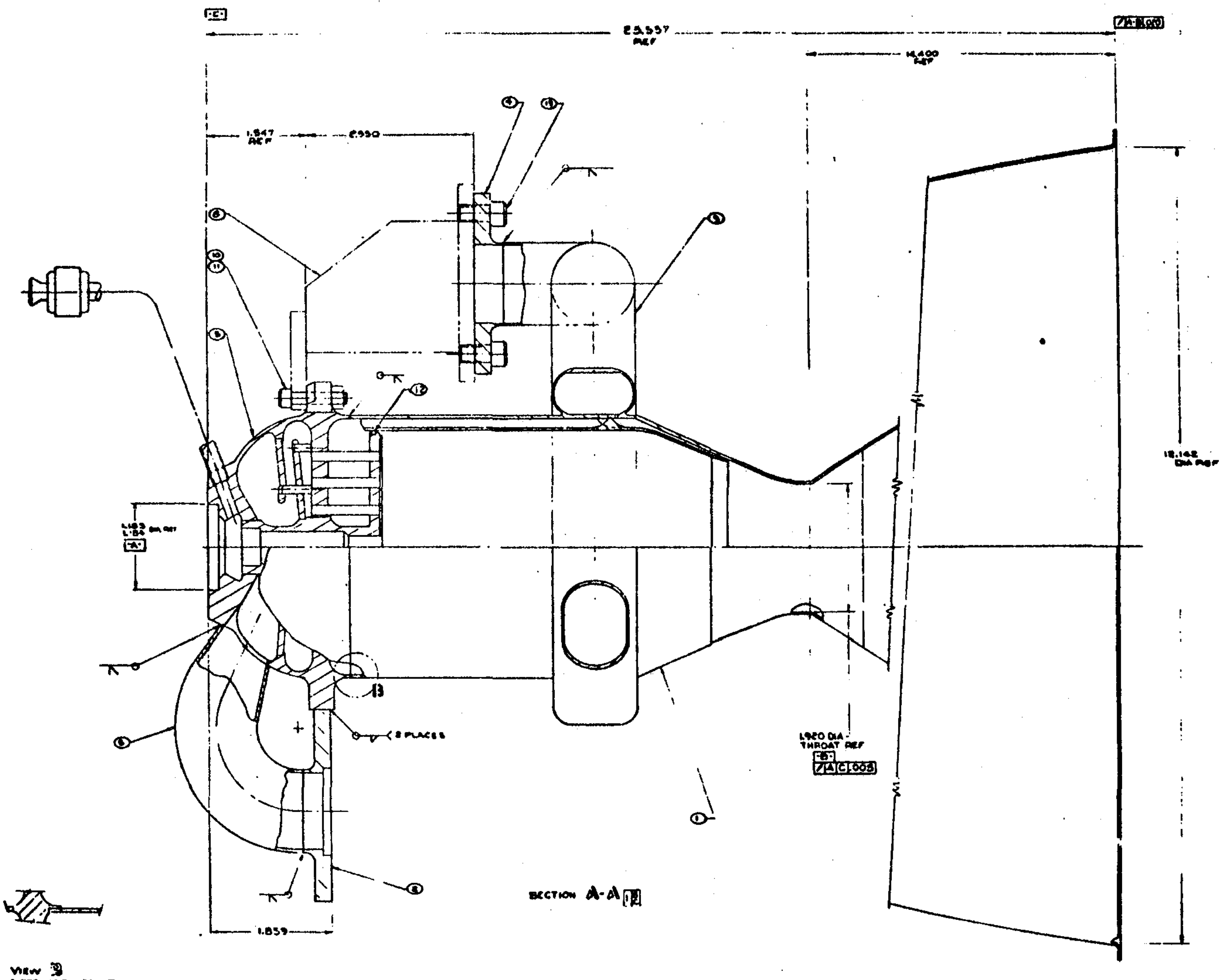


Figure 4-7. Integrated Thruster Assembly (ITA)

Table 4-11. ITA Design Summary

Design Characteristics	
Thrust	6672 N (1500 lb_f)
Chamber Pressure	207 N/cm^2 (300 psia)
Mixture Ratio	4.0
Pressure at Inlet to Valves	276 N/cm^2 (400 psia)
Fuel Flow Rate	
Regen and Injector	247 g/sec (.545 lb/sec)
Fuel Film Coolant	65.8 g/sec (.145 lb/sec)
Total	313 g/sec (.69 lb/sec)
Oxidizer Flow Rate	1252 g/sec (2.76 lb/sec)
Fuel Temperature	130°C (250°R)
Oxidizer Temperature	208°C (376°R)
Igniter Fuel Flow Rate	
Core	.726 g/sec (.0016 lb/sec)
Coolant	4.26 g/sec (.0094 lb/sec)
Total	4.99 g/sec (.011 lb/sec)
Igniter Oxidizer Flow Rate	32.66 g/sec (.072 lb/sec)
Igniter Core MR	45
Igniter Overall MR	6.55
Geometry	
Throat Diameter	4.88 cm (1.92 in.)
Exit Diameter	30.73 cm (12.1 in.)
Chamber Contraction Ratio	3.3
Nozzle Exit Area Ratio	40:1
Chamber L*	43.18 cm (17 in.)
Overall Length	74.68 cm (29.4 in.)
Overall Length (less exciter/spark plug)	61.37 cm (24.16 in.)
Fwd End Clearance Diameter	33.78 cm (13.3 in.)
Dimension of Cylinder Enclosing ITA	74.68 x 36.32 cm (29.4 x 14.3 in. Dia)
Weights (Design)	
ITA (incl. Main Propellant Valves)	14.016 kg (30.9 lb)
Main Propellant Valves	7.257 kg (16.0 lb)
ITA (less valves)	6.758 kg (14.9 lb)
Thrust Chamber (Incl. Insulation)	3.933 kg (8.67 lb)
Injector	1.887 kg (4.16 lb)
Igniter	.939 kg (2.07 lb)
Design Performance	
Specific Impulse	
Steady State	4266 N-sec/kg (435 lb_f-sec/lb_m)
Pulsing @ MIB	3923 N-sec/kg (400 lb_f-sec/lb_m)
MIB	222 N-sec (50 lb-sec)
Response (electrical signal to 90% thrust)	.050 sec

longest firing duration made with the ITA was 513 sec, (14) the ITA weight was 6.895 kg (15.2 lbm) exclusive of valves, (15) the cycle life goal was not met due to correctable mechanical errors, not design errors, and (16) premature chamber failure was the result of icing, not design error.

4.3 PLUG CLUSTER ENGINE PERFORMANCE DATA

The plug cluster engine design was evaluated for Space Tug type applications on NASA Contract NAS 3-20109 (Reference 5). The engine offers many features including: (1) competitive payload when compared to high pressure engines such as the ASE, (2) increased payload length due to the shortness of the engine, (3) design flexibility that will allow fail-operational modes for manned missions, and (4) long life, demonstrated components that will provide low cost, maintenance-free operation far in excess of the ASE and RL-10.

Pertinent data for the plug cluster engine are summarized in table 4-12.

Table 4-12. Plug Cluster Engine Data (Cluster of ITA-Type Modules)

	LOX/LH_2		
Thrust, lb_f	15,000		
Chamber Pressure, psia	500		
Area Ratio (Ae/At)	894		
Weight, lb	428		
Length, in.	37*		
Life, cycles	1,200**		
Mixture Ratio	5.0	5.5	6.0
Specific Impulse, sec	465.2	465.9	466.6

*Compared to 55 in. for RL10 on Baseline Space Tug.
**Compared to 190 cycles for the RL10 IIB and 300 cycles for the ASE.

5.0 ENGINE CONSULTING DATA

This section provides consulting data on: (1) a 40,000-pound thrust plug cluster engine, (2) a 70:30 LOX/CH_4: LOX/LH_2 dual expander engine, and (3) a throttled 70:30 dual expander engine.

5.1 PLUG CLUSTER ENGINE

A conceptual design for a 40,000-pound thrust plug cluster engine (PCE) was evaluated for the Space Tug baseline vehicle (Diameter = 14.7 feet). Summary data were previously supplied for a 15,000-pound thrust engine (Fourth Report entitled "Advanced Technology Forecast," dated 27 October 1978). Data for both engines are summarized in table 5-1.

A 40K conceptual design utilizes 26 thrusters, but otherwise resembles the 10-thruster 15K PCE. It seems reasonable, therefore, to assume a constant thrust-to-weight ratio for estimating the weight of the larger engine. Indications are that the 40K engine will possess a higher thrust-to-weight, since the thrusters are essentially mounted directly to the vehicle at the LOX tank centerline, eliminating the need for the thrust mount.

The weight data cited for the 15K and 40K plug cluster engines in table 5-1 are for a minimum valve system, which is probably not acceptable at this time for a man-rated system. A 50 to 100 pound weight penalty might be appropriate to place the PCE on the same basis as the ASE-type and expander cycle OTV engines (cf. Fifth Report entitled "Consulting Data," dated 20 December 1978). However, the plug cluster performance data are probably conservative by several seconds, compared to the candidate OTV engines. Utilization of the data as presented may, therefore, provide a fair comparison between engines.

An interesting feature of the 40K PCE is that the engine length is -15.9 inches compared to 37.1 inches for the 15K PCE and 55 inches for the RL10, when measured from the gimbal plane of the baseline Space Tug. In other words, the 40K PCE barely extends beyond the aft end of the LOX tank.

5.2 70/30 DUAL EXPANDER ENGINE

Parametric data are presented in table 5-2 and figures 5-1 and 5-2 for a dual expander engine with a 70% LOX/CH_4: 30% LOX/LH_2 thrust split.

Throttling the LOX/CH_4 stream tube by 20% amounts to the approximate Mode I vacuum thrust shown in table 5-2.

Table 5-1. Plug Cluster Engine Data Summary

PARAMETER	- ENGINE - 15K	40K
Vacuum Thrust, LB	15,000	40,000
Vacuum Is*, Sec	465.9	466.9
Chamber Pressure, PSIA	500	500
Mixture Ratio, O/F	5.44	5.43
Engine Area Ratio, AE/AT	890	600
Thruster Area Ratio, AE/AT	500	180
Number of Thrusters	10	26
Engine Diameter, In	132	170
Base Diameter, In	75	131
Engine Length, In	37.1	-15.9
Thruster Length, In	67.2	50.3
Engine Weight, LB	428	1141

*SIMPLIFIED JANNAF METHODOLOGY: CONSERVATIVE VALUES

Table 5-2. Tripropellant Dual-Expander Engine Preliminary Operating Specifications Design Point Thrust Split: 70% LOX/CH_4, 30% LOX/LH_2

	STREAM TUBES LOX/CH_4	STREAM TUBES LOX/LH_2	MODE I COMBINED LOX/CH_4 & LH_2	MODE II LOX/LH_2
Sea-Level Thrust, Lb.	425,600	182,400	608,000	
Vacuum Thrust, Lb.	465,390	208,790	674,180	216,710
Sea-Level Specific Impulse, Sec.	339.1	387	352.2	-
Vacuum Specific Impulse, Sec.	370.8	443	390.5	459.8
Total Flow Rate, Lb/Sec.	1255.09	471.32	1726.41	471.32
Mixture Ratio	3.6	7.0	4.20	7.0
Oxidizer Flow Rate, Lb/Sec.	982.24	412.40	1394.6	412.40
Fuel Flow Rate, Lb/Sec.	272.85	58.92	331.8	58.92
Chamber Pressure, PSIA	6,000	3,000	-	3,000
Nozzle Area Ratio	70	50	60.5	127
Mixture Ratio	3.6	7.0	4.20	7.0
Throat Area, $In.^2$	39.68	35.93	75.61	35.93
Nozzle Exit Area, $In.^2$	2,777	1,796	4,573	4,573
THROTTLED ENGINE				
Vacuum Thrust, LB	372,310	208,790	581,100	-
Total Flow Rate, Lb/Sec	1,004	471	1,475	-
Chamber Pressure, PSIA	4,800	3,000	-	-

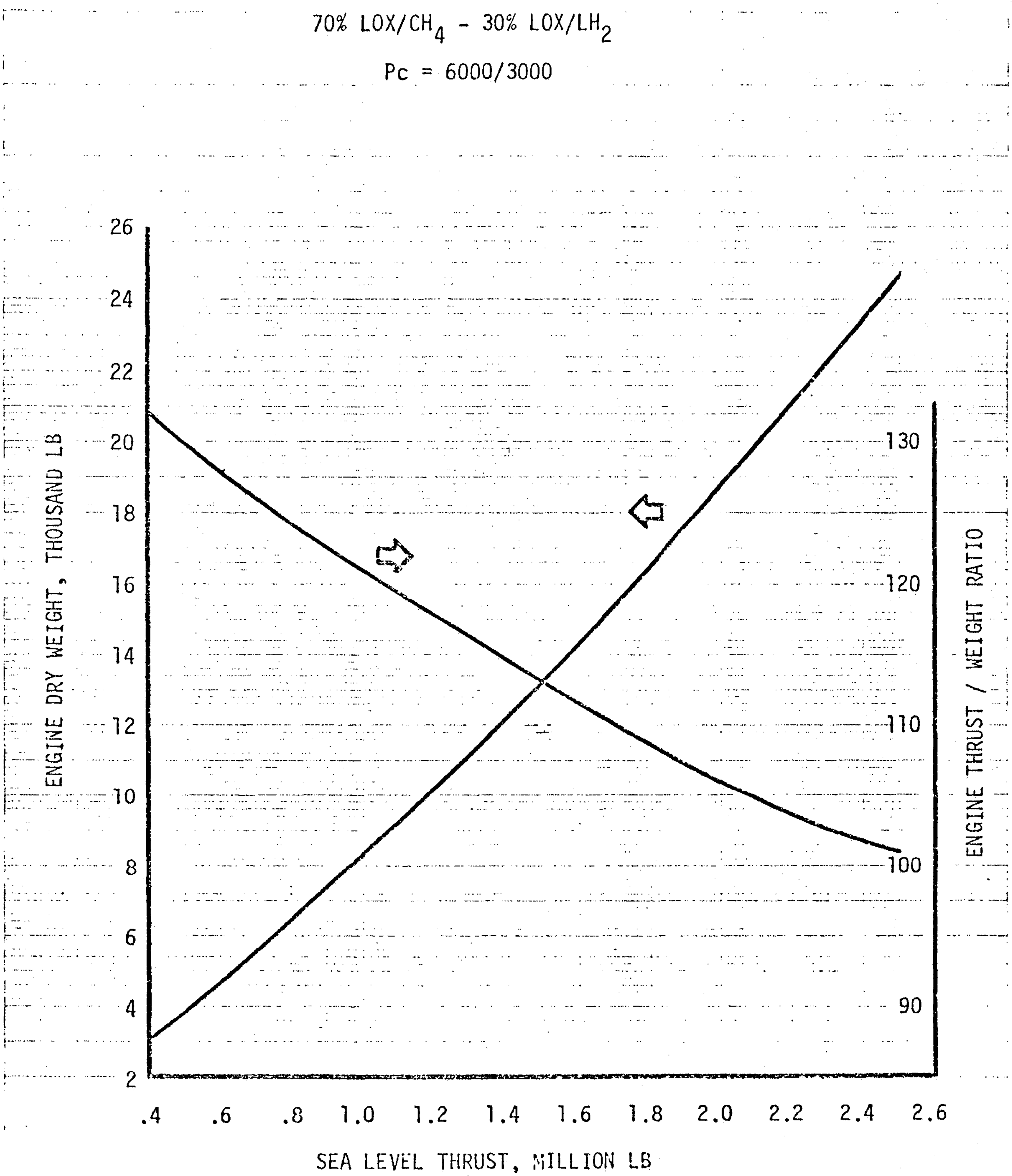


Figure 5-1. Dual Expander Engine Weight Parametrics

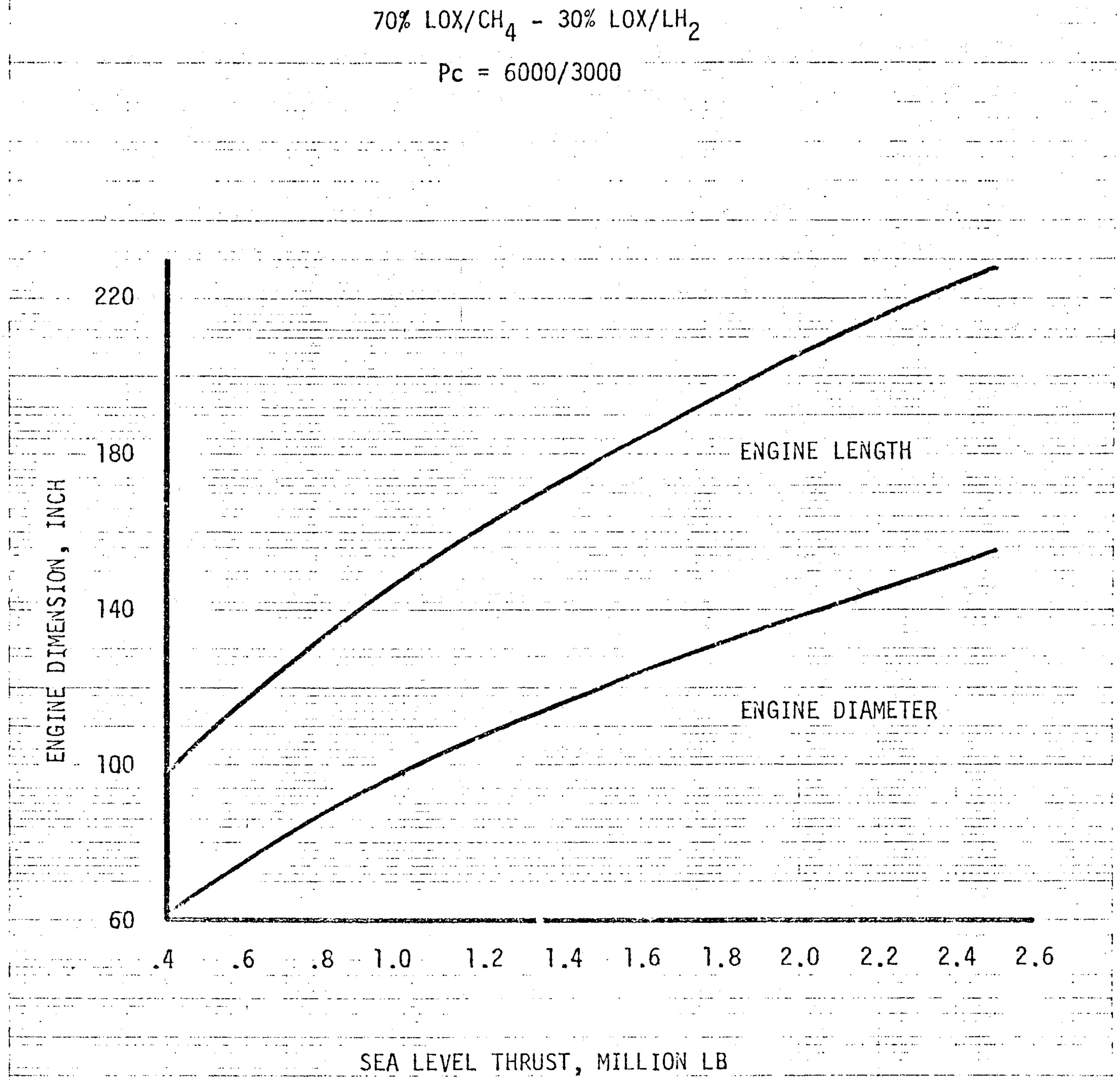


Figure 5-2. Dual Expander Envelope Parametrics

6.0 REFERENCES

1. "Technology Requirements for Future Earth-To-Geosynchronous-Orbit Transportation Systems, LOX/Methane Engine Parametric Data", Prime Contract NAS 1-15301, Subcontract N-500601-9109, Aerojet Liquid Rocket Company, 5 May 1978.

2. "Technology Requirements for Future Earth-To-Geosynchronous-Orbit Transportation Systems, LOX/Methane Engine Parametric Data, Supplement #1", Prime Contract NAS 1-15301, Subcontract N-500601-9109, Aerojet Liquid Rocket Company, 24 May 1978.

3. "Technology Requirements for Future Earth-To-Geosynchronous-Orbit Transportation Systems, Cost Data and Technical Update", Prime Contract NAS 1-15301, Subcontract N-500601-9109, Aerojet Liquid Rocket Company, 30 June 1978.

4. Luscher, W.P. and Mellish, J.A., "Advanced High Pressure Engine Study for Mixed-Mode Vehicle Applications", Final Report NASA CR-135141, Contract NAS 3-19727, Aerojet Liquid Rocket Company, January 1977.

5. O'Brien, C.J., "Unconventional Nozzle Tradeoff Study", Final Report NASA CR-159520, Contract NAS 3-20109, Aerojet Liquid Rocket Company, July 1979.

APPENDIX B

WORK BREAKDOWN STRUCTURE

TABLE OF CONTENTS

1.0 COSTING METHODOLOGY AND GROUNDRULES

The costing methodology and groundrules used in this study DDT&E are summarized as follows:

- o Methodology
  - DDT&E & TFU developed using Boeing PCM
  - operations labor costs based on HHLV, SPS & shuttle derivative studies
- o Key Groundrules
  - 1977 dollars
  - contractor charges without fee
  - only program support based on shuttle user charges
  - indirect costs based on typical industry charges
  - propellant costs based on JSC estimates
    - o LH_2 = \$0.731/lb LO_2 = \$.018/lb CH_4= \$.188/lb

TFU costs were generated parametrically and used to build up LCC's in conjunction with vehicle operational characteristics and mission model requirements. Operations costs were based on operations analysis performed during Shuttle Derivative Vehicle and Solar Power Satellite studies (ref. 1 and 2).

The cost estimates for this study were generated using the Boeing-developed Parametric Cost Model (PCM). The PCM is a semiautomated technique that has been used successfully on previous studies such as Future Space transportation System Analysis (FSTSA), Heavy Lift Launch Vehicle, Shuttle Derivative Vehicle, and Space Solar Power activities. A summary of this methodology is as follows:

1)	Short turn around time	Investigate many alternatives in time available
2)	Minimum of descriptive inputs	Can use early program definition where big gains in cost reduction are most available
3)	Take account of "off-the-shelf" and "modified' hardware	Save development costs
4)	Hardware redundancy levels	Cost effective redundancy level
5)	Material type choices	Material selection cost impact

6)	Hardening or not	Cost effects of hardening
7)	Variable test hardware quantities	Affords cost effective design of ground and flight test program
8)	Variable level of development and production spares	Spares costs reflect needed inventory and maintenance level
9)	Tooling is function of production quantity and production rate	Tooling reflects production plan
10)	GSE is based on number of sets needed	GSE reflects facilities plan (e.g., number of launch sites)
11)	Segregates DDT&E and production costs	Identifiy costs by program phase for scheduling and funding purposes
12)	Cost and manhour data provided at subsystem and cost element level	Facilitates detailed trades and indicates manpower levels involved
13)	Selectable learning curves at major component level	Develops production costs based on component level learning curve analysis

The PCM Provides a high degree of cost visibility since it is very similar in approach to detailed cost estimating. PCM compares to several other costing models as follows:

Feature/parameter	Boeing PCM	Aerospace	Econo-metrics	KOELLE	RCA Price
Working units	Manhours	Dollars	Dollars	Manhours	?
Level of hardware manhour/cost visibility	Subsystem	Subsystem	Subsystem	System*	Subsystem
Level of manhour/cost element visibility					
Total DDT&E	Yes	Yes	No	Yes	Yes
First unit	Yes	Yes	Yes	Yes	Yes
System engineering	Yes	Yes	No	No	Yes
System test	Yes	Yes	No	No	No
Software engineering	Yes	No	No	No	No
Quality control	Yes	No	No	No	No
Assembly and Checkout	Yes	Yes	No	No	No
Factory labor	Yes	No	No	No	Yes
Tooling	Yes	Yes	No	No	Yes
Design engineering	Yes	No	No	No	Yes
Developmental shop	Yes	No	No	No	Yes
Management	Yes	Yes	No	No	Yes
Support equipment	Yes	Yes	No	No	Yes
Facility workload	No	No	No	Yes	No
Length of prog effects	Yes	No	No	Yes	Yes
Off-the-shelf hardware effect	Yes	Limited	No	No	Yes
Existing design modification effect	Yes	Limited	No	No	Yes

*With the exception of one subsystem area; i.e., liquid rocket engines

The PCM estimates costs beginning with the major component level (level 6 of the WBS) and builds upward to obtain the total program cost. Cost estimations are based on physical and performance parameters at the hardware level and programmatic parameters (quantities, learning curves, production rates, etc.) at the project level. This methodology thus mirrors the actual approach used to develop and produce aerospace hardware. Boeing historical data collected in the Estimating Information System (EIS) data bank provide the raw information from which functional man-hour estimating relationships (MER) are formed. These MER's are based upon strong statistical correlations occurring in all

Boeing space programs and relate program inputs to the PCM internal working logic. In addition, each major functional area (e.g., project engineering, developmental shop, etc.) making up Boeing' organizational mix is represented and interrelated in the model. The role of these functional areas is ultimately expressed in terms of the man-hours required for each to fulfill the objectives of the program. Using man-hours instead of dollars allows construction of accountable estimates because it (1) eliminates the need to normalize for inflation, (2) allows construction of estimates in terms of either "constant" or "then year" dollars by simply applying the appropriately adjusted labor rates and pricing factors associated with the program's time span, and (3) allows use of large amounts of functional man-hour data accumulated by Boeing from actual programs.

The buildup of DDT&E costs from the constituent functional categories is diagrammed in figure 1. Judgement is required to evaluate system complexity of the subsystem being designed in order to select the correct MER. The procedure used to establish production costs is similar to that used for the design and development phase and is, in fact, implemented in the same PCM program.

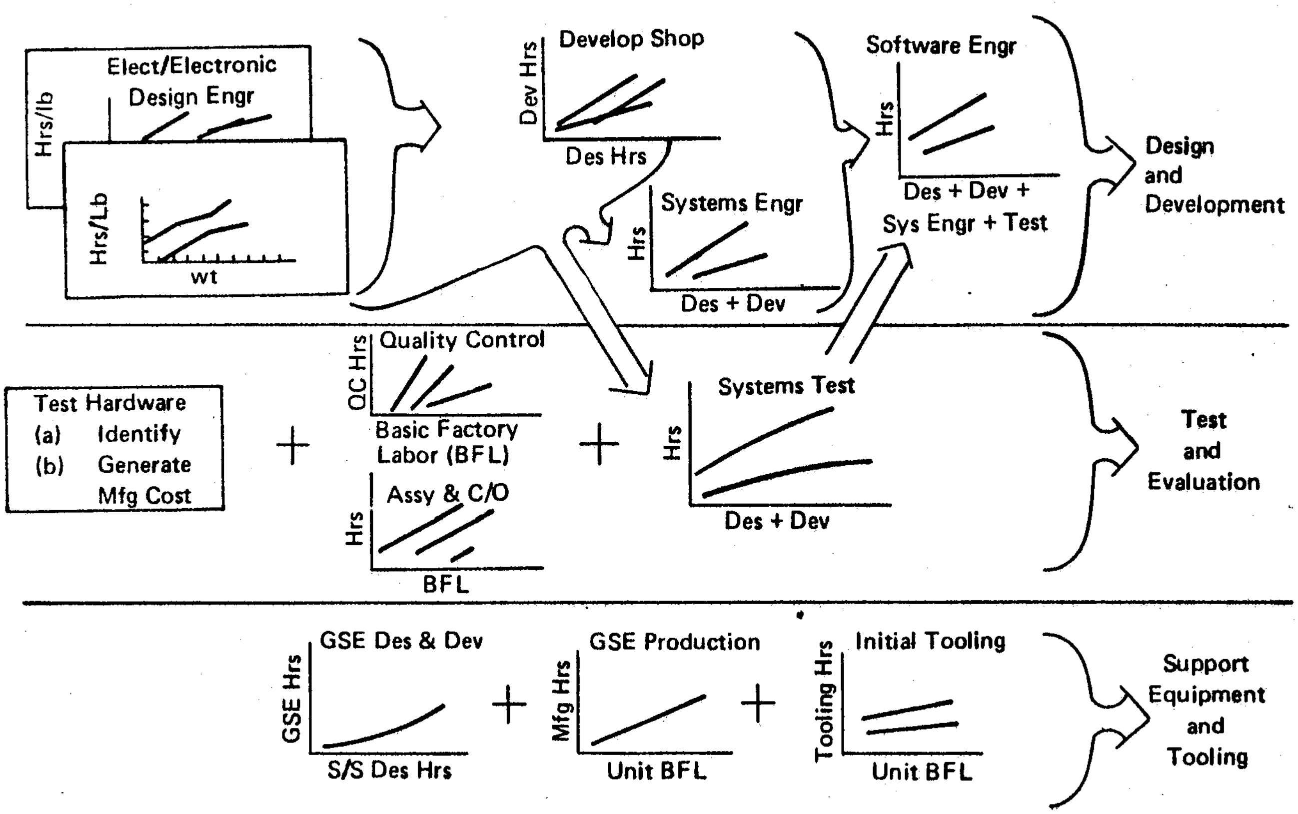


Figure 1. Boeing PCM Methodology (DDT&E)

The Work Breakdown Structure (WBS) used in costing the vehicles is shown in figure 5. It is a two-dimensional matrix formed by the vehicle hardware elements and the programmatic phases and functions. The following dictionary defines each of the WBS programmatic elements.

Mature Industry Cost Approach

For those items needed at mass production rates, we have used mass production cost estimating. The relationships are illustrated in figures 2 and 3. Aerospace cost experience follows a "learning" or improvement curve. (Most of the improvement comes from learning how to make the production plan work. Mechanics learn quickly.) Typical experience is an 85% curve; unit #2N will cost 85% of unit #N. 727 jetliner production experience shows that this type of projection is good well beyond the 1000th unit. Aerospace estimates are based on historical correlations of manhours, element physical characteristics, and complexity. They are made at the subsystem or subassembly level. Despite a contrary reputation, the basic estimating procedures are accurate. Aerospace cost variances can generally be traced to pricing and procurement practices, and most significantly to requirements and design changes, rather than to inability to estimate cost.

A mass production process is facility and equipment intensive rather than labor intensive. It does not follow an aerospace-type improvement curve. Historical correlations indicate a labor intensiveness relationship as shown in figure 3. A mass production processes reaches its labor cost plateau during the process shakedown period and then improves no further unless the process is changed.

The overall mature industry cost anlysis methodology used in this study is shown in figure 4. The aerospace first unit costs are run through a mature industry anlysis that applies production rate factors according to the production rate required for each system element.

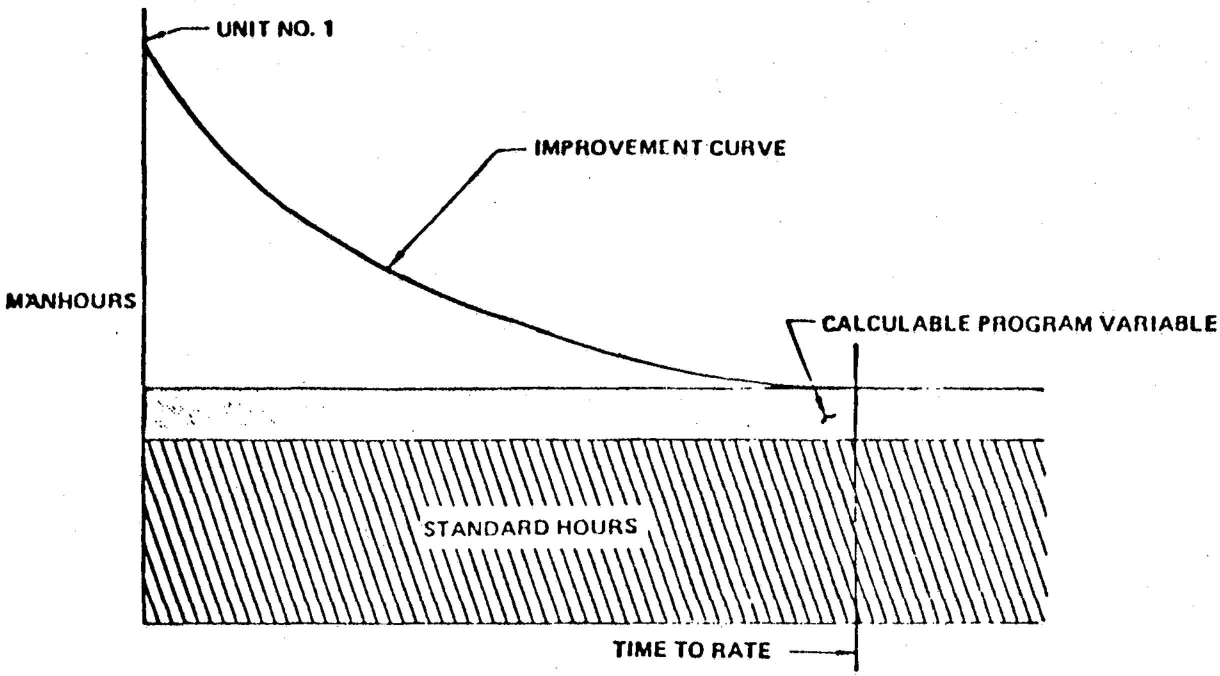


Figure 2. Program Cost Baseline

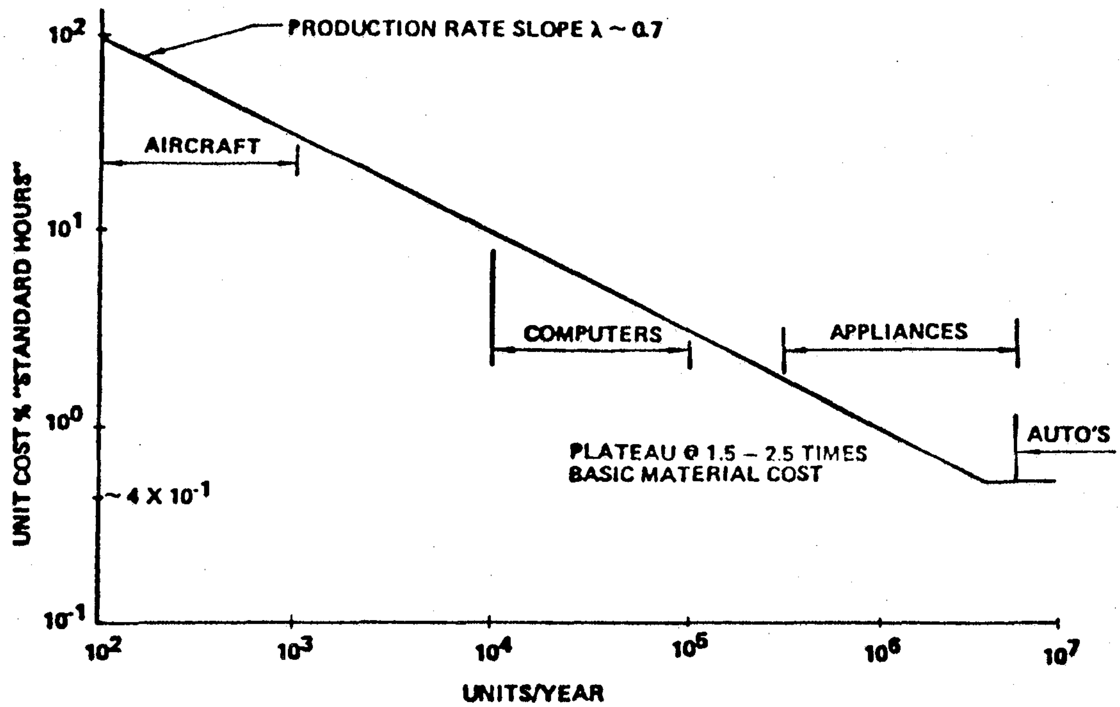


Figure 3. Mature Industry: Production Rate Curve

The mature industry costing approach was developed during SPS studies by Dr. Joe Gauger based on information developed during IR&D analyses of design-to-cost, experienced costs for commercial aircraft and other systems, and statistical correlations for financial and production factors for a wide variety of commercial industries.

SPS-1682

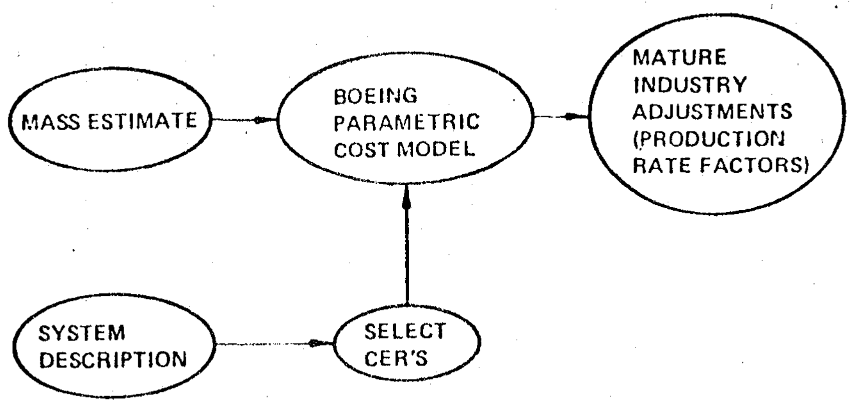


Figure 4. Cost Analysis Methodology

PHASE		PROGRAM 2000																
		DDT&E 2100								PRODUCTION 2200				OPERATIONS 2300				
Function			Engineering 2120			Manufacturing 2130		Test 2140				Manufacturing 2230		Operations Support 2310		Launch Support 2320		
Sub Function		Program Management	Systems Engineering & Integration	Software Engineering	Design & Development	Developmental Tooling & STE	Test Hardware & Spares	System Test Operations	Flight Test Operations	Program Management	Sustaining Engineering	Production Tooling & STE	Flt. Hardware & Initial Spares	Program Support	Spares Procurement	Operations	Propellant	Other
WBS ELEMENT	WBS 110	2110	2121	2122	2123	2131	2132	2141	2142	2210	2220	2231	2232	2311	2312	2321	2322	2323
TOTAL VEHICLE	01-00-00	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
VEHICLE INT. SYSTEM	01-01-00		●						●									
STAGE 1	01-02-00	●	●	●	●	●	●	●		●	●	●	●		●			
AEROSURFACES	01-02-01				●		●						●		●			
TANKAGE	01-02-02				●		●						●		●			
BODY STRUCTURE	01-02-03				●		●						●		●			
THERMAL PROTECTION	01-02-04				●		●						●		●			
LANDING SYS.	01-02-05				●		●						●		●			
PROPULSION	01-02-06				●		●						●		●			
A.P.S. [1]	01-02-07				●		●						●		●			
R.C.S.	01-02-08				●		●						●		●			
PRIME POWER	01-02-09				●		●						●		●			
ELECT. CONV./DIST.	01-02-10				●		●						●		●			
HYD./SURFACE CONTROL	01-02-11				●		●						●		●			
AVIONICS	01-02-12				●		●						●		●			
E. C. S.	01-02-13				●		●						●		●			
PERSONNEL/PAYLOAD	01-02-14				●		●						●		●			
GSE	01-02-15				●		●						●		●			
PROPELLANT	01-02-16																●	
STAGE II	01-03-00	●	●	●		●		●		●	●	●	●		●			
AEROSURFACES	01-03-01				●		●						●		●			
TANKAGE	01-03-02				●		●						●		●			
BODY STRUCTURE	01-03-03				●		●						●		●			
THERMAL PROTECTION	01-03-04				●		●						●		●			
LANDING SYS.	01-03-05				●		●						●		●			
PROPULSION	01-03-06				●		●						●		●			
A.P.S. [1]	01-03-07				●		●						●		●			
R.C.S.	01-03-08				●		●						●		●			
PRIME POWER	01-03-09				●		●						●		●			
ELECT. CONV./DIST.	01-03-10				●		●						●		●			
HYD./SURFACE CONTROL	01-03-11				●		●						●		●			
AVIONICS	01-03-12				●		●						●		●			
E. C. S.	01-03-13				●		●						●		●			
PERSONNEL/PAYLOAD	01-03-14				●		●						●		●			
GSE	01-03-15				●		●						●		●			
PROPELLANT	01-03-16																●	

[1] Consists of OMS For Second Stages, Flyback Propulsion for First Stages

Figure 5. Work Breakdown Structure

2.0 PROJECT AND PHASES DEFINITION

2000 Program

This element sums all efforts and materials required for the design, development, production and operation of the total vehicle project.

2100 Design, Development, Test and Evaluation (DDT&E)

Consists of the "one time" cost of designing, developing, testing and evaluating the vehicle system. Specifically, it includes; mission analysis and requirements definition; mission and support hardware functional definition and design specifications, design engineering, interface analysis and engineering integration, developmental shop support, test hardware manufacture and functional, qualification and flight test effort; also includes special test equipment and development tooling, logistics, training (that not covered in operations), developmental spares and other program peculiar costs not associated with repetitive production. This element is subdivided into the following functions:

2110 Program Mangement
2120 Engineering
2130 Manufacturing
2140 Test

2200 Production

<u>Recurring</u> - These are the recurring costs of production program management, fabrication, assembly, checkout, quality control inspection and acceptance tests related to multiple units of hardware production. Also included in production costs are initial spares, multiple sets of ground support equipmet (recurring GSE) and sustaining engineering. This element is subdivided into the following functions:

2210 Program Management
2220 Sustaining Engineering
2230 Manufacturing

<u>Non-recurring</u> - Non-recurring production costs cover the costs of production tooling, sustaining tooling and special test equipment (STE).

2300 Operations

Relates to the effort and materials to put the vehicle system into service operate it and maintain it. This category covers such operational items as receipt of mission hardware elements (i.e., stages, engines, etc.), processing, testing and integration; launch operations, flight or mission operations and control, recovery, sustaining spares and inventory control, maintenance and propellants and other consumables.

This element is subdivided into to the following functions:

2310 Operations Support

2320 Launch Support

3.0 FUNCTION DEFINITIONS

2100 DDT&E

2110 Program Management

Contractor - This element includes that effort during DDT&E relating to the contractor(s) technical and business management of the program. It incudes the effort of decision making, directing and assuring that plans are implemented and products are designed and tested by "doing" organizationas and then controlling the program in a cost effective and technically competent manner. Specific areas of effort are:

Planning and Control
Finance Management
Contracts Management
Engineering and Developmental Manufacturing Management
Quality Assurance Management
Configuration Management
Data Management
Facilities Coordination

NASA - Customer program management relates to the overall direction and control of the program. This function includes the decision making and planning required to determine objectives, select the concept to fulfill the objective, assign responsibilities and coordinate program participants within NASA, plan the product's utilization, create schedules, direct contractors, control funding and develop the products operational plan.

2120 Engineering

This DDT&E element includes all efforts and materials associated with analysis, design, development, evaluation and redesign for specified hardware element items. This element is subdivided into the following lower elements:

2121 System Engineering and Integration
2122 Software Engineering
2123 Design and Development

2130 Manufacturing

This DDT&E element includes the efforts and materials required to produce the various items of test hardware required by the program which include inspection, assembly and checkout of tools, parts, material, subassemblies and assemblies. The testing of this hardware is accomplished under system operations. The test articles considered under this element include development models, engineering models, design verification units, qualification models, structural test units, thermal models, mechanical models and prototypes.

2131 Developmental Tooling and STE

2132 Test Hardware and Spares

2140 Test

This DDT&E element relates to the manpower and miscellaneous materials needed to conduct the testing of the ground and flight test articles. It also includes all efforts and materials required during flight test operations. This accumulation category is further difined under:

2141 Systems Test Operations

2142 Flight Test Operations

2200 Production

2210 Program Management

This element includes that effort during production relating to the technical and business managment of the SDV production program. It includes the effort of decision making, directing and assuring that production plans are implemented by the manufacturing, quality control and material organizations.

2220 Sustaining Engineering

Starts after the First Article Configuration Inspection (FASI) of the first operational unit and continues to the end of the program. Includes correction of design errors, testing, updating of drawings, liaison with Manufacturing, Quality Control (Q.C.), and Materiel organizations, and design of company and customer initiated changes.

2230 Manufacturing

This element includes all recurring efforts and materials associated with the production of flight hardware, initial spares, tooling and special test equipment (STE). The subfunctions of this cost element are:

2231 Production (Rate) Tooling

2232 Flight Hardware and Spares

2300 Operations

2310 Operations Support

Includes (a) the required Program Support effort at the hardware/mission control centers, (b) the reusable spares procurement (which are the replenishment spares) and the refurbishment hardware required, and (c) the cost of all expendable hardware.

2320 Launch Support

This operations element includes all those efforts and materials required for launch support. This element includes those efforts and materials associated with the receipt of the stages, engines, etc. at the launch site and the processing, testing, and integration required for preparation and launching of the vehicle, excluding any payload integration activities.

4.0 SUBFUNCTION DEFINITIONS

2100 DDT&E

2110 Program Managment

211C No Subfunctions

2100 DDT&E

2120 Engineering

2121 Systems Engineering and Integration

This element includes the activities directed at assuring a totally integrated engineering effort. It includes the effort to establish system, subsystem, GSE and Test requirements and criteria, to define and integrate technical interfaces to optimize total system definition and design, to allocate performance parameters to the subsystem level, to identify, define and control interface requirements between system elements, to monitor design and equipment to determine contract end item (CEI) compliance, to provide and maintain inertial properties analyses, support and documentation, to develop and maintain system specification to provide parts, standards and materials and processes surveillance and to integrate product assurance activities. Fundamental to this WBS element is the documentation of system-level design requirements as derived from NASA-established requirements and guidelines and through functional analyses.

Specific areas of effort are:

- System Design and Integration
- Configuration
- Flight Hardware Requirements
- Operations Requirements
- GSE Requirements
- System Test Requirements
- Mass Properties

Interfaces

Materials, Processes and Standards

Product Assurance

Service and Maintenance Requirements

2122 Software Engineering

This element includes the costs of the design, development, production, checkout, maintenance and delivery of computer software. Included are test, on-board and mission or flight software.

2123 Design and Development

This DDT&E element includes all efforts associated with analysis, design, development, evaluation and redesign necessary to translate a performance specification into a design. Specifically included are:

- Subsystem Design Engineering
  - o Subsystem Functional Definition and Design Specifications
  - o Design of Components and Hardware Assemblies
  - o Intra Subsystem Engineering Integration
- Developmental Shop Support
  - o Component, Assembly and Subsystem Mockups and Breadboards
  - o Materials and Processes Verification
- Subsystem Test
  - o Breadboard and Functional Tests
  - o Subsystem Qualification Tests

2100 DDT&E

2130 Manufacturing

2131 Developmental Tooling and STE

This DDT&E element includes all efforts and materials required to produce the various items of required ground and flight test hardware. This element includes the time expended on, or chargeable to, such operations as fabrication, processing, subassembly, final assembly, reworking and modification and installation of parts

and equipment. Included are those costs chargeable to the acceptance testing, quality control program, and assembly as related to ground test hardware. Ground test hardware includes such items as static and dynamic test models, thermal and (if required) firing test articles and the qualification test unit. Flight test hardware includes the flight-test vehicles and their associated GSE required for the flight test program. This element also includes the costs of developing and documenting requirements for, and the fabrication, assembly, test, storage, delivery and accountability of spare components, assemblies, or subsystems to be used in support of the ground test and flight program.

2100 DDT&E

2140 Test

2141 System Test Operations

This DDT&E element includes all efforts and materials required for System Test Operations. Included are tests on all systems test hardware, assemblies, subsystems, and systems to determine operational characteristics and compatibility with the overall system and its intended operational/nonoperational environment. Such tests include design feasibility tests, design verification tests, reliability tests, etc. Also included are tests on systems and integrated systems to verify whether they are unconditionally suitable for their intended use. These tests are conducted on hardware or final designs that have been produced, inspected and assembled and priced under test hardware category (2132).

2142 Flight Test Operations

This element includes all efforts and materials required to support the DDT&E flight test program. This item includes the operation of the mission control facilities and equipment. Included is mission control monitoring which provides the information required to control, direct and evaluate the mission from prelaunch through recovery. This operations element also includes all efforts and materials required to support launch and recovery operations during the DDT&E flight test program. Included are those efforts and materials associated with the receipt of the stages, engines, etc. at the launch site and the processing, testing and integration required for launching of the mission test hardware. This element does not include payload integration. Included are subelements such as ground operations (including recovery) and propellant operations.

2200 Production

2210 Program Management

221X No Subfunctions

2200 Production

2200 Sustaining Engineering

Includes both the systems engineering and design engineering required to support the production phase of the program.

222X No Subfunctions

2200 Production

2230 Manufacturing

2231 Production Tooling and STE

Production tooling is "hard" tooling designed for repetitive use in fabricating and assembling recurring production units. This element includes the fabrication of production tooling and those sustaining efforts necessary to facilitate production and to resolve production problems involving tooling and STE. Production tooling includes sustaining and replenishment tooling.

2232 Flight Hardware and Spares

This element includes all efforts and materials required to produce production flight units. This item includes time expended on, or chargeable to, such operations as fabrication, processing, subassembly, final assembly, reworking, modification, and installation of parts and equipment (including Government furnished equipment (GFE)). Included are those costs chargeable to the acceptance testing, quality control program, and assembly as related to flight units. Also included in this element are the costs of developing and documenting requirements for, and the fabrication, assembly, cost, storage, delivery and accountability of spare components, assemblies or subsystems that will be produced in the production phase of the program and be used as the initial "lay in" of spares to fill the beginning inventory

stocks. Excluded are bin production spares of small items such as fasteners, electronic parts, etc. Included within this element is the cost of developing and inventory-control documentation system and the costs of shipping and distribution of spares to maintain designated inventory levels.

2300 Operations

2310 Operations Support

Includes the required Program Support effort at the hardware/mission control centers, the reusable hardware spares procurement which are the replenishment spares and the refurbishment hardware required, and the cost of all expendable hardware including initial production spares inventory.

2311 Program Support

Includes the hardware/mission control center effort and their associated contracted effort to support the operations phase of the program. Mission planning, mission control, sustaining engineering and program management activities for hardware delivery in direct support of the program.

2312 Spares Procurement

Includes the cost of producing and inventorying replenishment/refurbishment hardware and the depot maintenance manpower to support the reusable hardware maintenance during operations. Both line replaceable and shop replaceable units are included.

2320 Launch Support

This operations element includes all those efforts and materials required for launch support, from recovery of the vehicle through launching. This element includes those efforts and materials associated with the receipt or recovery of the vehicle elements at the launch site and the processing, testing, and integration required to prepare the vehicle for launching, excluding any payload integration activities.

2321 Operations

Includes all the effort and materials required for the receipt of the vehicle hardware at the launch site and the processing, testing, and integration required to prepare for launching of the mission hardware. This effort includes the manpower associated with the:

- Processing, testing, and integration of the flight hardware.
- Operation and maintenance of launch related ground support equipment.
- Offline ground systems activities (shops, labs, etc.) required to support the vehicle turnaround activities.
- GSE sustaining engineering effort to support modification design and configuration control of all launch site related ground support equipment.
- Recovery of the vehicle and all inspections and refurbishment required to return it to operational status.
- Producing and inventorying the launch site related ground support equipment replenishment/refurbishment spares.

2322 Propellants

Includes all flight propellant costs at the launch site, excluding SRB solid propellants such as all fuels and oxidizers, pressurants, purging gases and fluids to support the operational phase of the program. These costs reflect annual base requirements in addition to total flight requirements.

2323 Other

Includes all other program direct at the launch site. These costs include:

- Photo, central timing and ordnance effort
- Purchase of supplies and materials
- Operation of the local barge and port facilities.

REFERENCES

1. "Shuttle Derivative Vehicles Study - Operations, Systems, and Facilities," Contract NAS8-32395, Final Report, dated December 1977.

2. "Solar Power Satellite Systems Definition Study," Part I Final Report Contract NAS9-15196, dated July, 1977.

APPENDIX C
WEIGHT ESTIMATING METHODOLOGY
WINGED LAUNCH VEHICLES

WEIGHT ESTIMATING METHODOLOGY
WINGED LAUNCH VEHICLES

An iterative point-design weight estimating approach was used throughout the study. The logic flow for this approach, as applied to winged launch launch vehicles, is presented in figure 1.

The starting point for the interative process is the calculation of top level vehicle characteristics consistent with ascent performance requirements and an estimate of the vehicle mass fraction. The top level characteristics are defined as those which are necessary to evolve a configuration 3-view drawing, namely; gross weight, propellant weight, payload weight, inert weight, and ascent engines definition. Depending on the time and data base available, point design weight analyses are conducted on major structural components such as main tankage and shell structures. Geometry data (areas) from the 3-view drawing and the results of any point design weight analyses are entered in the weight calculation notes. These notes, which are approximately 30-35 pages in length for an SSTO, HLLV Orbiter, or HLLV Booster, address every group in the group weight and balance statement and, in some instances, address items at the subgroup level and lower (see launch vehicle configuration descriptions in main body of report). The notes are in a simple fill-in-the-blanks format, complete with a brief description of, or reference to, supporting rationale.

The weight calculation notes are exercised in conjunction with the group weight and balance statement in mission sequential format. The objective is to define and compare the maximum allowable dry weight (obtained by a top-down weights analysis starting with the vehicle gross weight) and the calculated dry weight (obtained by a bottom-up weights analysis of subsystem dry weights).

The top down weights analysis is undertaken first and yields the following: usable propellant requirements for propulsion systems other than ascent propulsion (OMS, RCS, Flyback), start entry weight, and landing weight. In addition, consistent with landing wing loading limitations, the wing area on the 3-view drawing is revised and the area of other aerosurfaces adjusted as deemed necessary. Lastly, the bottom-up weights analysis is undertaken and the resulting calculated dry weight is compared with the maximum allowable dry weight. If the weight difference is considered acceptable, either the dry weight margin allowance or the payload weight is adjusted to compensate for it. If the

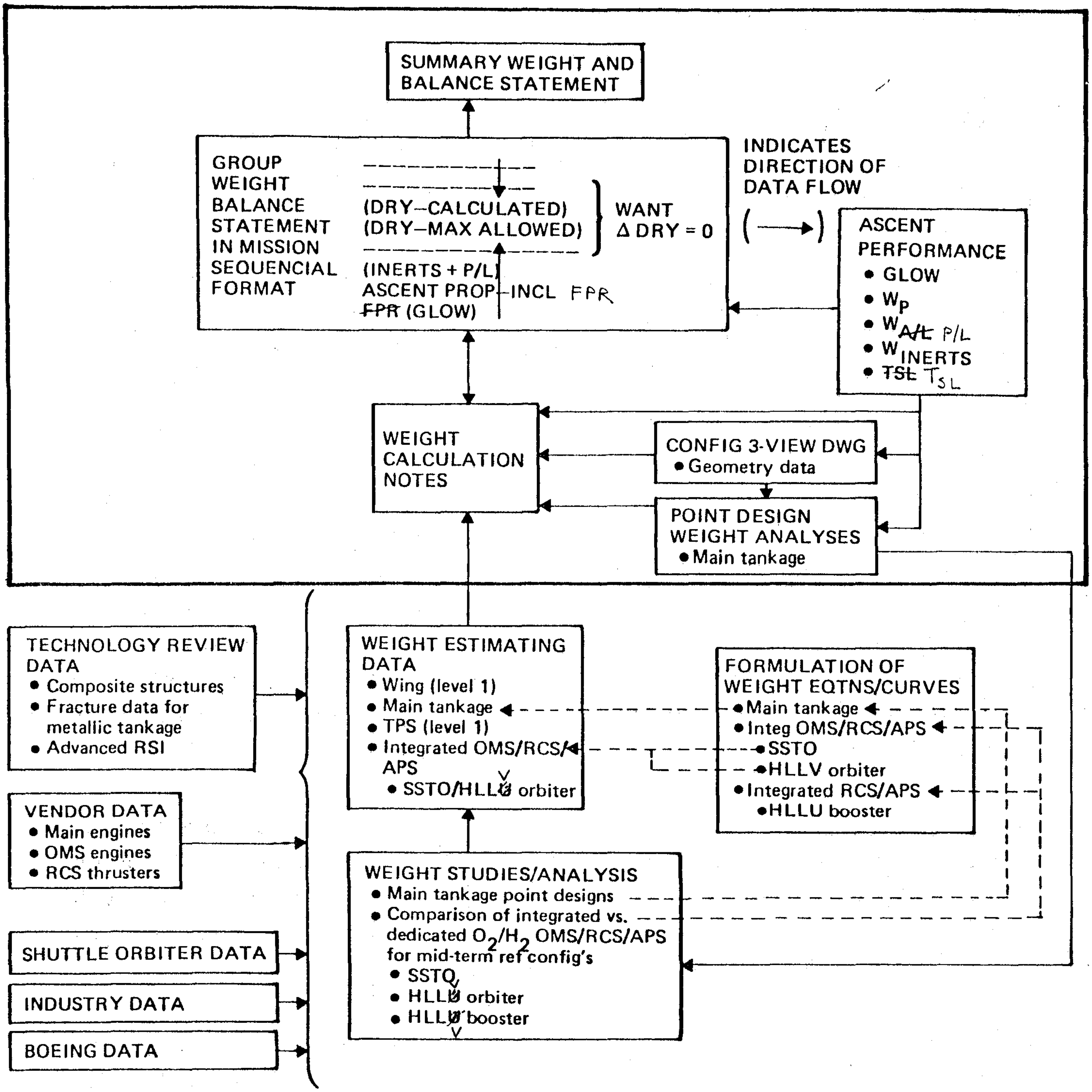


Figure 1. Logic Flow For Weight Estimating Winged Launch Vehicles

weight difference is unacceptable, the vehicle inert weight is changed (but not ascent propellant weight, payload weight or ascent thrust) and the weights analyses iterated until an acceptable delta dry weight condition exists.

At this point, though the ascent performance is either slightly excessive or slightly deficient, the vehicle mass fraction is valid for the ascent propellant weight, payload weight, and ascent thrust considered. This mass fraction is then used as the basis for a new mass fraction estimate with which to start a repeat effort at final vehicle sizing. For the HLLV, final vehicle sizing is accomplished first for the Orbiter, then for the Booster.

Figure 1 also depicts the manner in which the available data bank is maintained and used to support the weight estimating procedures in the weight calculation notes. As an example, Appendix D presents the results of a weight evaluation and comparison of dedicated and integrated $0_2/H_2$ subsystems (OMS, RCS, APS) for the midterm configurations. Based on this study data, weight scaling equations were derived for both dedicated and integrated O_2/H_2 subsystems and are included in the weight calculation notes (which contain methods for defining all input data for the equations). The weight scaling equations for the integrated O_2/H_2 subsystems are also included in Appendix D.

APPENDIX D

WEIGHT EVALUATION

AND

COMPARISON OF DEDICATED AND INTEGRATED

O_2/H_2 SUBSYSTEMS

TABLE OF CONTENTS

LIST OF FIGURES

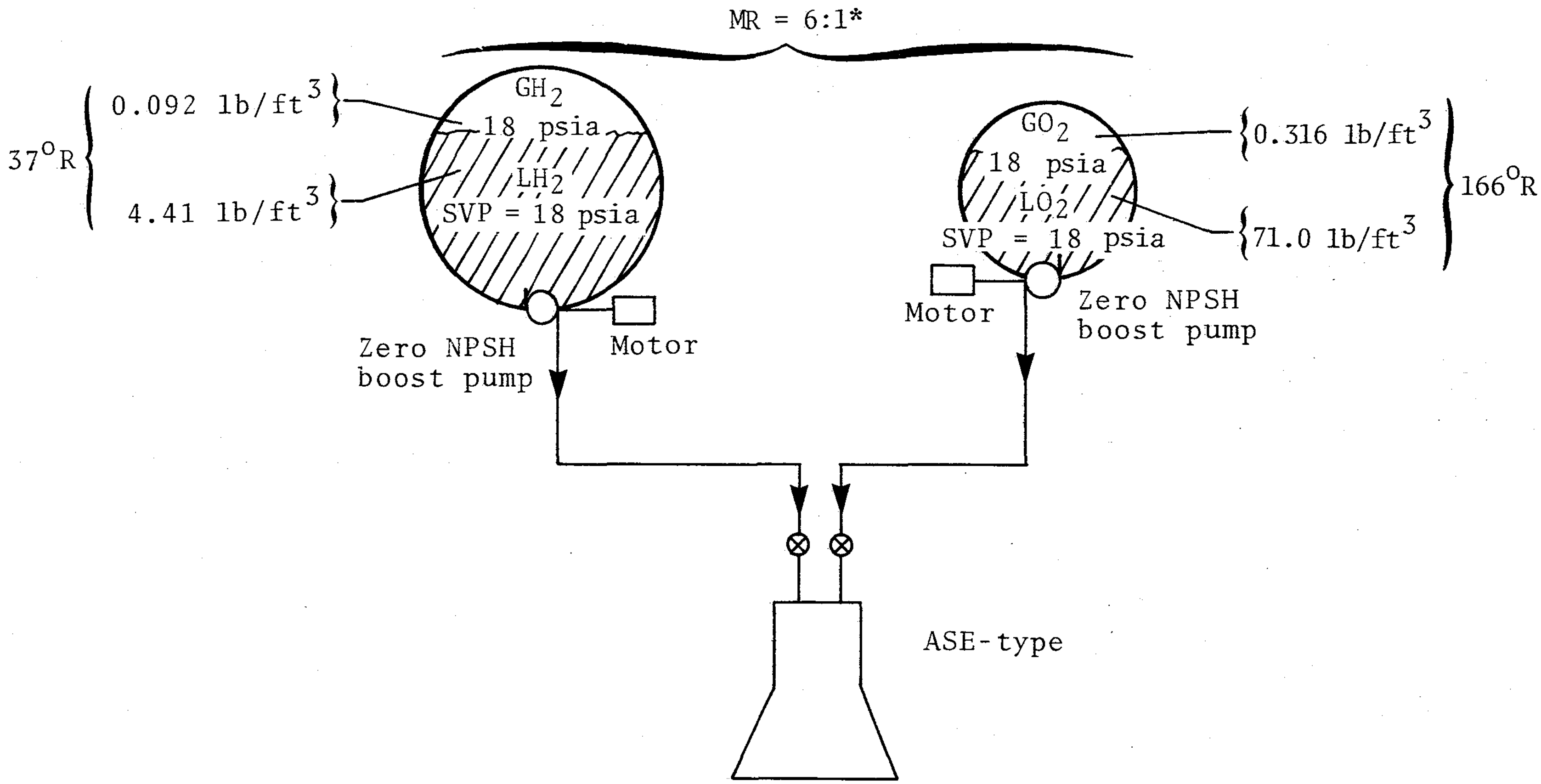
LIST OF TABLES

1.0 INTRODUCTION/SUMMARY

This appendix presents summary data from the study effort to evaluate and compare weight data for dedicated and integrated O_2/H_2 subsystems for the normal growth technology vehicles SSTO, HLLV, and POTV. For the SSTO and HLLV, the auxiliary power unit (APU) power requirements and hydrazine requirements were updated, the APU working fluid was changed from N_2H_4 to O_2/H_2, and the dry weights and residuals weights for the dedicated OMS, RCS, and APS (auxiliary power system) were subjected to indepth analyses. For the POTV, the responsibility for providing for GEO and LEO terminal phase initiation maneuvers was transferred from the RCS to the MPS (in keeping with improved main engine life projections), the fuel cell power requirements, and the dry weights and residuals weights for the dedicated MPS, RCS, and EPS (electrical power system) were subjected to indepth analyses. Using the detailed weights definition of the dedicated subsystems, it was possible to define the detailed weights definition of the integrated subsystems. Pertinent summary data is identified in the following paragraphs.

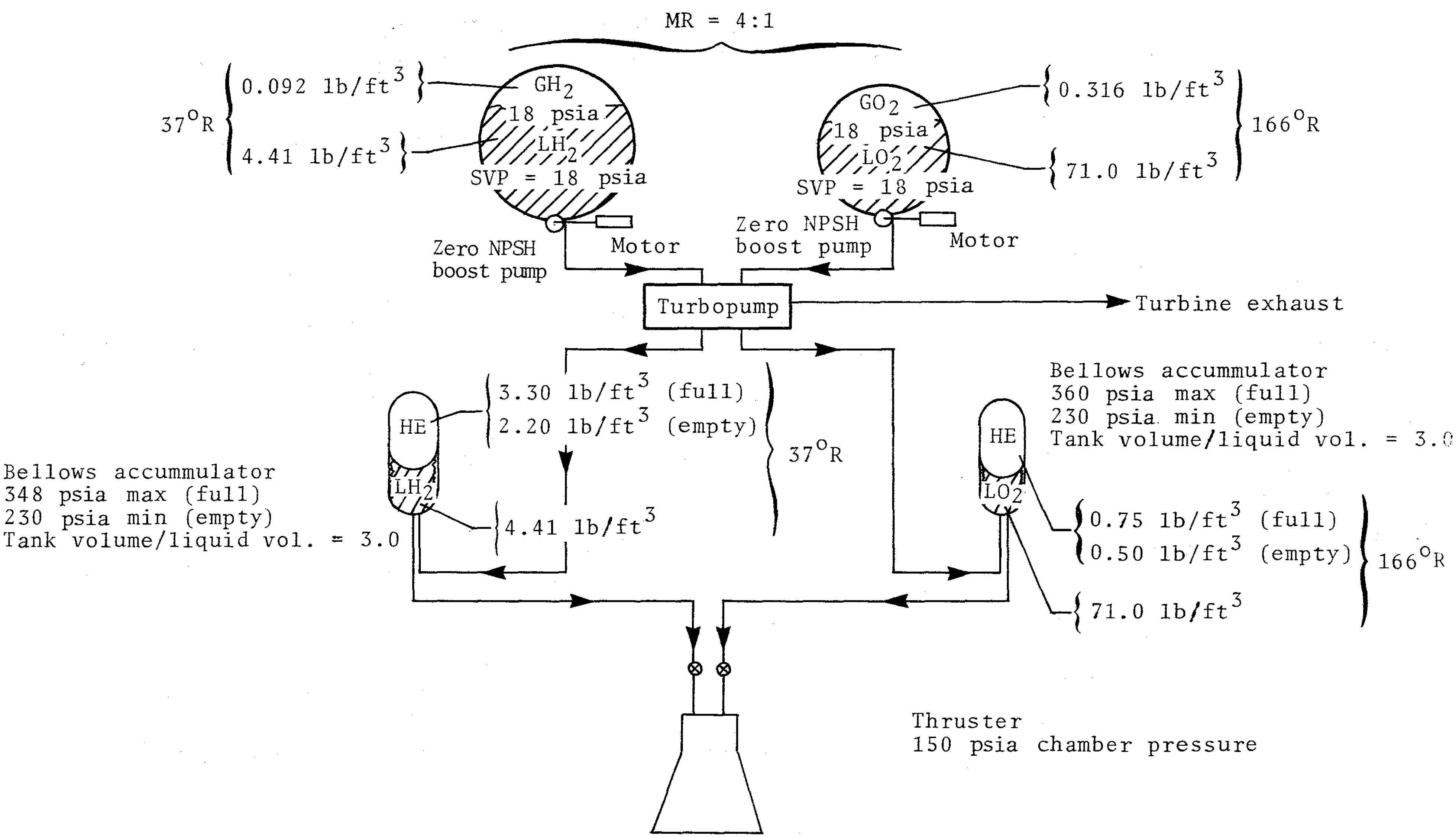
2.0 SSTO AND HLLV VEHICLES

Simplified schematics of dedicated O_2/H_2 OMS/RCS/APS subsystems are presented in figures 2-1, 2-2 and 2-3, respectively. Simplified schematics of integrated O_2/H_2 OMS/RCS/APS subsystems for the SSTO and HLLV Orbiter, and integrated O_2/H_2 RCS/APS subsystems for the HLLV Booster, are presented in figures 2-4 and 2-5, respectively. The updated APU power requirements and N_2H_4 weight previously referred to are presented in table 2-1, including a note indicating the weight ratio of O_2/H_2 to N_2H_4. Primary weight estimating criteria for the O_2H_2 subsystems is presented in table 2-2. Detailed weight comparison of dedicated and integrated O_2H_2 OMS/RCS/APS subsystems for the SSTO and HLLV are presented in tables 2-3 and 2-4, respectively. Detailed weight comparisons of dedicated and integrated O_2/H_2 RCS/APS subsystems for the HLLV Booster is presented in table 2-5. Weight scaling equations for the foregoing integrated O_2/H_2 subsystems are presented in table 2-6.



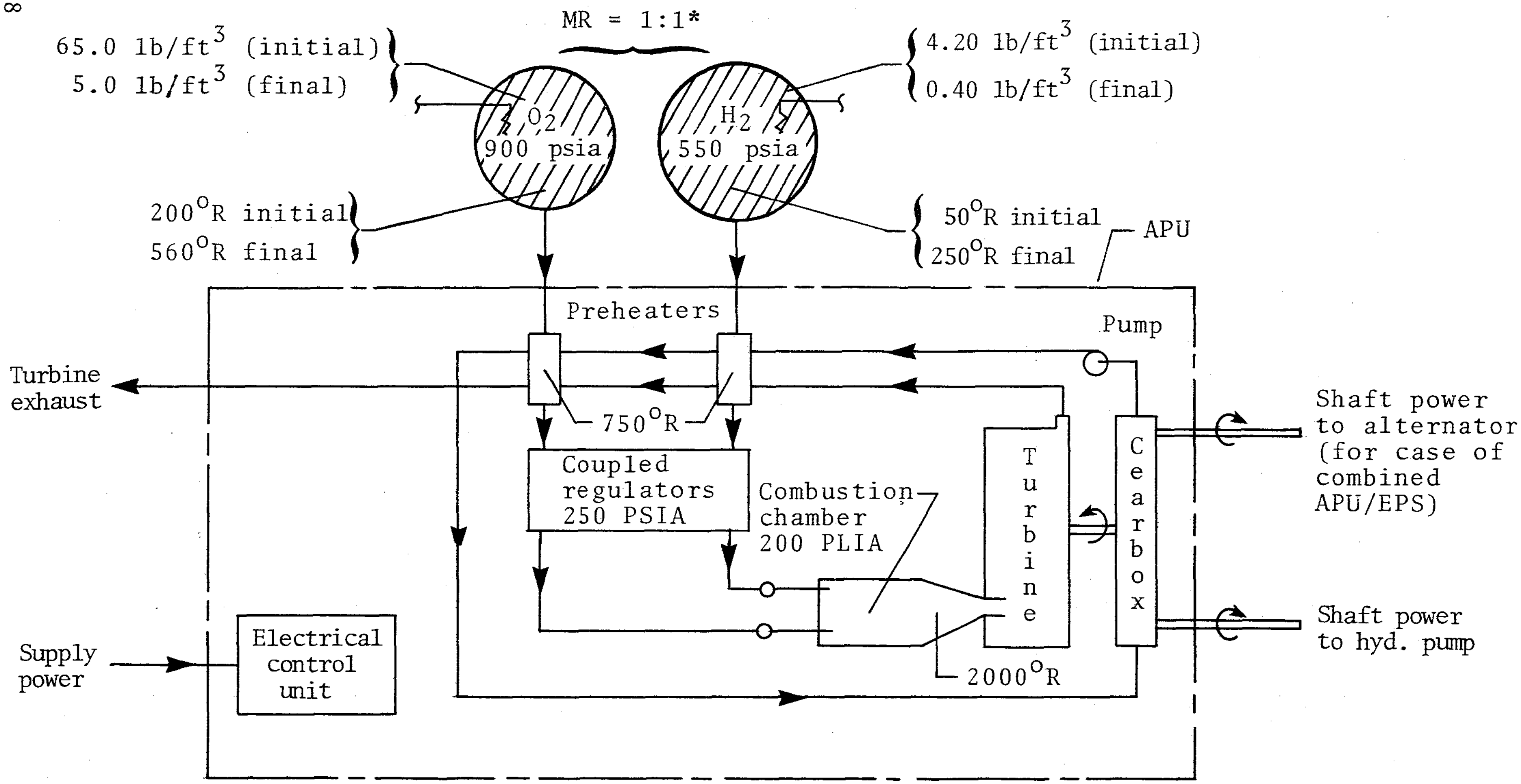
* Usable oxidizer to usable fuel.

Figure 2-1. Simplified Schematic of LO_2/LH_2OMS SSTO and HLLV Orbiter.



* Usable oxidizer to usable fuel

Figure 2-2. Simplified Schematic of LO_2/LH_2 RCS SSTO and HLLV Pumped Hydrogen/Pumped Oxygen



* Usable oxidizer to usable fuel.

Figure 2-3. Simplified Schematic of O_2/H_2APU Subsystem SSTO and HLLV (Supercritical Storage of O_2/H_2)

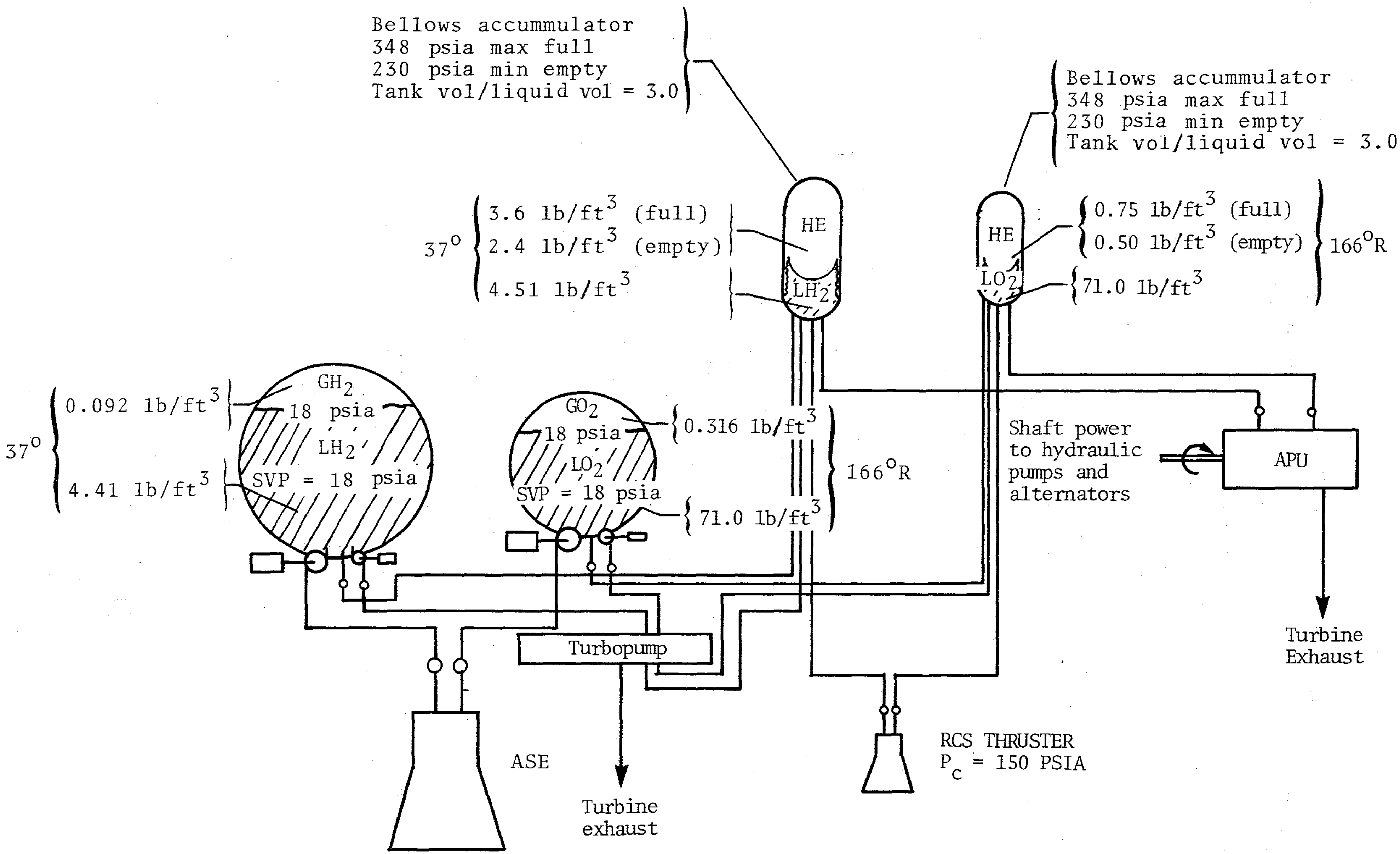


Figure 2-4. Simplified Schematic of Integrated LO_2/LH_2OMS/RCS/APS SSTO and HLLV Orbiter.

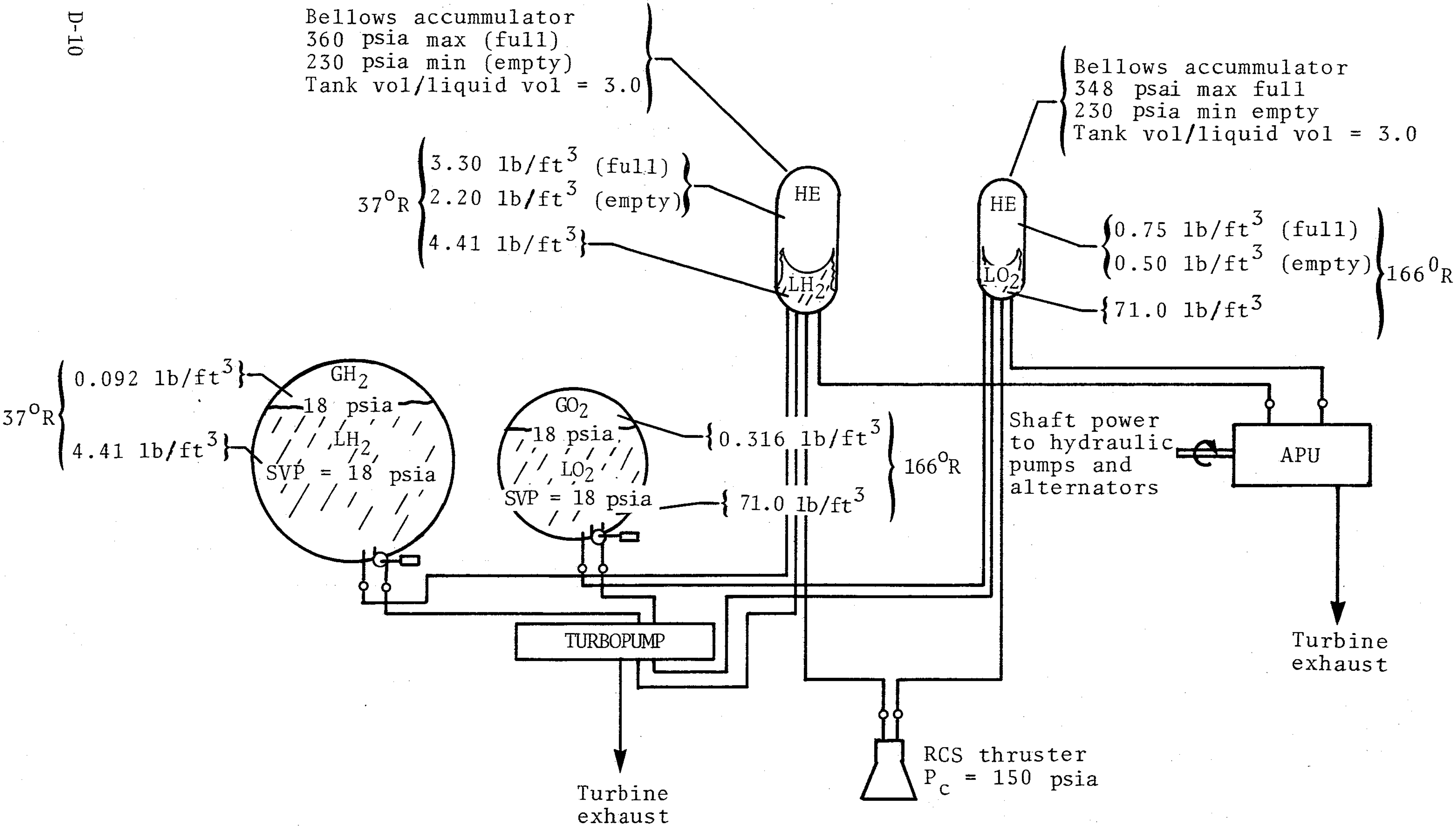


Figure 2-5. Simplified Schematic of Integrated LO_2/LH_2RCS/APS HLLV Booster.

Table 2-1. APU Power Requirements/Hydrazine Weight SSTO and HLLV

(MID-TERM UPDATE)

ITEM	SHUTTLE	SSTO	HLLV ORBITER	HLLV BOOSTER
BODY FLAP AREA, FT^2	136	870	1081	1081
ELEVON AREA, FT^2	413	730	890	925
RUDDER AREA, FT^2	97	345	370	436
START FLYBACK WING LOADING, LB/FT^2	--	--	--	83.3
LANDING WING LOADING, LB/FT^2	69.4	73.8	72.0	74.2
NUMBER OF MAIN ROCKET ENGINES	3*	10**	8*	13*
ELECTRICAL POWER, KW-HR [1]	--	50	50	10
APU PEAK POWER, HP: ENG. FLARING @LIFTOFF	360	--	--	--
APU PEAK POWER, HP: ENTRY STEERING	220	730	840	1040
APU PEAK POWER, HP: INSTALLED	405	930 [2]	1065 [2]	1320 [2]
HYDRAZINE USAGE-HYDRAULIC, LB	(500)	(1070)	(1300)	(1630)
PRELAUNCH/LIFTOFF/ASCENT	90 [3]	150	240	390
ON-ORBIT	30 [3]	50	60	--
ENTRY/LANDING	380 [3]	870	1000	--
ENTRY	--	--	--	620
FLYBACK/LANDING	--	--	--	620
HYDRAZINE USAGE-ELECTRIC, LB	(--)	(370)	(370)	(70)
PRE-LAUNCH/LIFTOFF/ASCENT		20	20	20
ON-ORBIT		330	330	--
ENTRY/LANDING		20	20	--
ENTRY		--	--	10
FLYBACK/LANDING		--	--	40
NOMINAL HYDRAZINE USAGE, LB	500	1440	1670	1700

[2] INCLUDES 20 HP PEAK ELECTRICAL

[1] DIVIDED EQUALLY BETWEEN 3 INDEPENDENT SYSTEMS, 2 OF WHICH ARE REQUIRED TO BE OPERATIONAL DURING ENTRY.

[3] CURRENT BEST ESTIMATE FOR DUE EAST MISSION. (R.T. CONRAD, 12/1/78)

*ALL GIMBALLED

**5 OF 10 GIMBALLED

NOTE: $W_{O2/H2} = 0.43 \times W_{N2H4}$

Table 2-2. Primary Weight Estimating Criteria for Dedicated/Integrated O_2/H_2 Subsystems [1] (SSTO and HLLV)

ENGINES (OMS):
- ASE-TYPE @20,000 LB TVAC EACH
- TOTAL INSTALLATED THRUST $\geq$ 5% OF VEHICLE WEIGHT @INSERTION
- NPSH OF LO-PRESS FUEL PUMP = 0.5 PSI
- NPSH OF LO-PRESS OXID. PUMP = 1.0 PSI

THRUSTERS (RCS):
- TOTAL INSTALLED THRUST = 17% OF VEHICLE WEIGHT @ENTRY
- NO. OF THRUSTERS:
  - FWD 14 (MAX OF 4 FIRED SIMULTANEOUSLY)
  - AFT 24 (MAX OF 6 FIRED SIMULTANEOUSLY)
  - TOTAL 38 (MAX OF 6 FIRED SIMULTANEOUSLY)

APU'S (APS):
- 3 O_2/H_2 UNITS
- INSTALLED WEIGHT = 1.17 LB/HP

AUXILIARY BATTERIES (APS):
- POWER REQUIREMENT: 10 AMP-HR, 400 VOLT
- $Ni\text{-}H_2$ @16 WATT-HR/LB

BOOST PUMPS/MOTORS (OMS,RCS):
- ZERO NPSH PUMPS
- ELECTRIC MOTORS
- REDUNDANCY:
  - OMS - NONE
  - RCS - 6 SETS {3 FUEL, 2 REQ'D; 3 OXID., 2 REQ'D}

PROPELLANT TANKS (OMS, RCS, APS):
- SPHERICAL
- 2219-T87
- 500 MISSION SERVICE LIFE REQUIREMENT

(CONT'D)

[1] SEE SIMPLIFIED SCHEMATICS AND APU MAX POWER ESTIMATES FOR ADDITIONAL DATA.

Table 2-2. (Continued)

BELLOWS ACCUMMULATORS (RCS):

- CYLINDRICAL
- 2219-T87 PRESSURE SHELL
- STAINLESS STEEL BELLOWS
- SERVICE LIFE REQUIREMENT
  - 25 MISSIONS, SSTO AND HLLV ORBITER
  - 50 MISSIONS, HLLV BOOSTER
- NO. OF ACCUMMULATORS: 2 FUEL, 2 OXID.
- TOTAL ACCUMMULATOR CAPACITY:
  - SSTO AND HLLV ORBITER:
    - 5% USABLE RCS PROP. (DEDICATED)
    - 5% USABLE RCS/APS PROP. (INTEGRATED)
  - HLLV BOOSTER:
    - 10% USABLE RCS PROP. (DEDICATED)
    - 10% USABLE RCS/APS PROP. (INTEGRATED)

PRESSURE SHELL PROOF FACTORS (OMS, RCS, APS):

	TANKS	ACCUM'S	
	SSTO & HLLV	SSTO & HLLV ORB.	HLLV BOOSTER
SERVICE LIFE REQ'T-MISSIONS	500	25	50
PRESSURE CYCLING-PER MISSION			
FULL DEPTH	1	0	0
PARTIAL	0	20	10
EQUIV. FULL DEPTH	1	2	1
PRESS. CYCLING-OPER. CONTINGENCY			
FULL DEPTH	10	0	0
PARTIAL	0	5	10
EQUIV. FULL DEPTH	10	0.5	1
DESIGN CYCLES (FULL DEPTH)	1020	101	102
STRESS INTENSITY RATIO			
LOWER BOUNDARY CURVE	0.43	0.63	0.63
PROOF FACTOR	2.3	1.6	1.6

THERMAL CONTROL (OMS, RCS, APS):

- VACUUM JACKETS ON TANKS, ACCUMMULATORS, AND LINES
- LIGHTWEIGHT JACKETS @ 1.5 LB/FT^2

Table 2-3. Detail Weight Comparison of Integrated vs Dedicated O_2/H_2 OMS/RCS/APS SSTO (All Weights in Pounds)

ITEM	REFERENCE DEDICATED SYSTEMS	REFERENCE INTEGRATED SYSTEMS
OMS	(4,240)	(4,525)
ENGINES & ACCESSORIES (2 ASE'S)	910	910
ZERO NPSH BOOST PUMPS/MOTORS	80	80
FUEL TANK	480	571
OXIDIZER TANK	280	308
PROPELLANT FEED, FILL & DRAIN	250	250
VENT/RELIEF-TANKS	200	200
PNEMATIC	100	100
PROPELLANT LOADING/MONITORING	30	30
THERMAL CONTROL	1,520	1,664
SUPPORTS/INSTALLATION	390	412
RCS	(4,056)	(3,440)
THRUSTERS-INCL. VALVES (38-2260 LBF)	1,240	1,240
ZERO NPSH BOOST PUMPS/MOTORS	33	36
TURBOPUMPS	70	75
FUEL TANK	125	--
OXIDIZER TANK	50	--
FUEL BELLOWS ACCUMMULATORS	366	420
OXID. BELLOWS ACCUMMULATORS	94	88
PROP. LINES-FEED, FILL & DRAIN	247	247
ISOLATION VALVES, ETC-FEED, FILL & DRAIN	150	150
COMPENSATORS	50	50
VENT/RELIEF-TANKS, ACCUMMULATORS	80	30
THERMAL CONTROL	1,185	790
SUPPORTS/INSTALLATION	366	314
APS	(3,340)	(1,773)
AUXILIARY POWER UNITS-INSTALLED (3)	1,090	1,090
BATTERIES	250	250
ALTERNATORS	30	30
FUEL TANK	906	--
OXID. TANK	94	--
REACTANT FEED, FILL & DRAIN	150	150
VENT/RELIEF-TANKS	90	--
THERMAL CONTROL	400	62
SUPPORTS/INSTALLATION-REACTANT SYSTEM	160	21
LUBE OIL COOLANT SYSTEM	-- 1	-- 1
EXHAUST SYSTEM	170	170
DRY WEIGHT-LESS MARGIN	11,636	9,738

1 INTERNAL TO APU'S.

(CONT'D)

Table 2-3. (Continued)

(ALL WEIGHT IN POUNDS)

ITEM	REFERENCE DEDICATED SYSTEMS	REFERENCE INTEGRATED SYSTEMS
(CONT'D)		
MARGIN	(1,165)	(973)
DRY WEIGHT	12,801	10,711
OMS RESIDUAL FLUIDS & GASES	(725)	(764)
TRAPPED PROPELLANT-FEED SYSTEM	355	355
TRAPPED PROPELLANT-ENGINES	60	60
FUEL BIAS	35	35
TRAPPED GH_2	120	143
TRAPPED GO_2	155	171
RCS RESIDUAL FLUIDS & GASES	(804)	(791)
TRAPPED PROP.-ACCUMMULATORS	22	22
TRAPPED PROP.-FEED, FILL & DRAIN	635	635
TURBOPUMP GG PROP.	41	50
TRAPPED GH_2	19	--
TRAPPED GO_2	16	--
HE IN FUEL ACCUMMULATORS	67	80
HE IN OXID. ACCUMMULATORS	4	4
APS RESIDUAL FLUIDS & GASES	(90)	(4)
TRAPPED REACTANT-TANKS	86	--
TRAPPED REACTANT-APU'S/LINES	4	4
OMS INFLIGHT LOSSES	(250)	(250)
PROP. FOR ENGINE START/STOP (5)	250	250
INERT WEIGHT	14,670	12,520

(CONT'D)

Table 2-3. (Continued)

(ALL WEIGHTS IN POUNDS)

ITEM	REFERENCE DEDICATED SYSTEMS	REFERENCE INTEGRATED SYSTEMS
(CONT'D)		
RESERVES	(2,920)	(2,052)
OMS - O_2 } MR=6:1	1,594	--
" - H_2	266	--
RCS - O_2 } MR=4:1	600	--
" - H_2	150	--
APS - O_2 } MR=1:1	155	--
" - H_2	155	--
OMS/RCS/APS - O_2 } RSS OF ABOVE	--	1,710
OMS/RCS/APS - H_2	--	342
NOMINAL PROPELLANT/REACTANT	(41,590)	(41,590)
OMS @MR=6:1	37,220	37,220
RCS @MR=4:1	3,750	3,750
APS @MR=1:1	620	620
TOTAL WEIGHT	59,180	56,162

Table 2-4. Detail Weight Comparison of Integrated vs Dedicated O_2/H_2 OMS/RCS/APS HLLV Orbiter (All Weights in Pounds)

ITEM	REFERENCE DEDICATED SYSTEMS	REFERENCE INTEGRATED SYSTEMS
OMS	(4,480)	(4,927)
ENGINES & ACCESSORIES (2 ASE'S)	910	910
ZERO NPSH BOOST PUMPS/MOTORS	80	80
FUEL TANK	510	653
OXIDIZER TANK	290	334
PROPELLANT FEED, FILL & DRAIN	310	310
VENT/RELIEF-TANKS	200	200
PNEUMATIC	100	100
PROPELLANT LOADING/MONITORING	30	30
THERMAL CONTROL	1,640	1,862
SUPPORTS/INSTALLATION	410	448
RCS	(4,758)	(3,876)
THRUSTERS-INCL. VALVES (38-2350 LBF)	1,281	1,281
ZERO NPSH BOOST PUMPS/MOTORS	34	34
TURBOPUMPS	71	80
FUEL TANK	192	--
OXIDIZER TANK	66	--
FUEL BELLOWS ACCUMMULATORS	564	601
OXID. BELLOWS ACCUMMULATORS	160	146
PROP. LINES-FEED, FILL & DRAIN	248	248
ISOLATION VALVES, ETC-FEED, FILL & DRAIN	150	150
COMPENSATORS	50	50
VENT/RELIEF-TANKS, ACCUMMULATORS	100	40
THERMAL CONTROL	1,407	894
SUPPORTS/INSTALLATION	435	352
APS	(3,720)	(2,031)
AUXILIARY POWER UNITS-INSTALLED (3)	1,180	1,180
BATTERIES	250	250
ALTERNATORS	30	30
FUEL TANK	1,056	--
OXID. TANK	109	--
REACTANT FEED, FILL & DRAIN	170	170
VENT/RELIEF-TANKS	100	100
THERMAL CONTROL	440	74
SUPPORTS/INSTALLATION-REACTANT SYSTEM	185	27
LUBE OIL COOLANT SYSTEM	-- 1	-- 1
EXHAUST SYSTEM	200	200
DRY WEIGHT - LESS MARGIN	12,958	10,834

1 INTERNAL TO APU'S.

(CONT'D)

Table 2-4. (Continued)

ITEM	REFERENCE DEDICATED SYSTEMS	REFERENCE INTEGRATED SYSTEMS
(CONT'D)		
MARGIN	(1,295)	(1,083)
DRY WEIGHT	14,253	11,917
OMS RESIDUAL FLUIDS & GASES	(940)	(1,001)
TRAPPED PROPELLANT-FEED SYSTEM	545	545
TRAPPED PROPELLANT-ENGINES	60	60
FUEL BIAS	40	40
TRAPPED GH_2	130	166
TRAPPED GO_2	165	190
RCS RESIDUAL FLUIDS & GASES	(872)	(835)
TRAPPED PROP.-ACCUMMULATORS	38	35
TRAPPED PROP.-FEED, FILL & DRAIN	589	589
TURBOPUMP GG PROP.	69	85
TRAPPED GH_2	31	--
TRAPPED GO_2	27	--
HE IN FUEL ACCUMMULATORS	112	121
HE IN OXID. ACCUMMULATORS	6	5
APS RESIDUAL FLUIDS & GASES	(105)	(4)
TRAPPED REACTANT-TANKS	101	--
TRAPPED REACTANT-APU'S/LINES	4	4
OMS INFLIGHT LOSSES	(150)	(150)
PROP. FOR ENGINE START/STOP (3)	150	150
INERT WEIGHT	16,320	13,907

(CONT'D)

Table 2-4. Cont.

ITEM	REFERENCE DEDICATED SYSTEMS	REFERENCE INTEGRATED SYSTEMS
(CONT'D)		
RESERVES	(3,580)	(2,388)
OMS - O_2 } MR=6:1	1,689	--
" - H_2	281	--
RCS - O_2 } MR=4:1	1,000	--
" - H_2	250	--
APS - O_2 } MR=1:1	180	--
" - H_2	180	--
OMS/RCS/APS - O_2 } RSS OF ABOVE	--	1,971
" " " - H_2	--	417
NOMINAL PROPELLANT/REACTANT	(46,370)	(46,370)
OMS @MR=6:1	39,380	39,380
RCS @MR=4:1	6,270	6,270
APS @MR=1:1	720	720
TOTAL WEIGHT	66,270	62,665

Table 2-5. Detail Weight Comparison of Integrated vs Dedicated O_2/H_2 OMS/RCS/APS HLLV Booster (All Weights in Pounds)

ITEM	REFERENCE DEDICATED SYSTEMS	REFERENCE INTEGRATED SYSTEMS
OMS	(--)	(--)
ENGINES & ACCESSORIES		
ZERO NPSH BOOST PUMPS/MOTORS		
FUEL TANK		
OXIDIZER TANK		
PROPELLANT FEED, FILL & DRAIN		
VENT/RELIEF-TANKS		
PNEMATIC		
PROPELLANT LOADING/MONITORING		
THERMAL CONTROL		
SUPPORTS/INSTALLATION		
RCS	(4,448)	(5,175)
THRUSTERS-INCL. VALVES (38-3170 LBF)	1,630	1,630
ZERO NPSH BOOST PUMPS/MOTORS	44	73
TURBOPUMPS	76	102
FUEL TANK	85	131
OXIDIZER TANK	34	38
FUEL BELLOWS ACCUMMULATORS	420	721
OXID. BELLOWS ACCUMMULATORS	106	122
PROP. LINES-FEED, FILL & DRAIN	260	265
ISOLATION VALVES, ETC-FEED, FILL & DRAIN	170	170
COMPENSATORS	70	70
VENT/RELIEF-TANKS, ACCUMMULATORS	70	70
THERMAL CONTROL	1,118	1,313
SUPPORTS/INSTALLATION	405	470
APS	(4,215)	(2,393)
AUXILIARY POWER UNITS-INSTALLED (3)	1,540	1,540
BATTERIES	250	250
ALTERNATORS	30	30
FUEL TANK	1,069	--
OXID. TANK	111	--
REACTANT FEED, FILL & DRAIN	210	210
VENT/RELIEF-TANKS	100	--
THERMAL CONTROL	460	84
SUPPORTS/INSTALLATION-REACTANT SYSTEM	195	29
LUBE OIL COOLANT SYSTEM	-- 1	-- 1
EXHAUST SYSTEM	250	250
DRY WEIGHT - LESS MARGIN	8,663	7,568

1 INTERNAL TO APU'S.

(CONT'D)

Table 2-5. (Continued)

ITEM	REFERENCE DEDICATED SYSTEMS	REFERENCE INTEGRATED SYSTEMS
(CONT'D)		
MARGIN	(870)	(760)
DRY WEIGHT	9,533	8,328
OMS RESIDUAL FLUIDS & GASES	(--)	(--)
TRAPPED PROPELLANT-FEED SYSTEM		
TRAPPED PROPELLANT-ENGINES		
FUEL BIAS		
TRAPPED GH_2		
TRAPPED GO_2		
RCS RESIDUAL FLUIDS & GASES	(812)	(933)
TRAPPED PROP.-ACCUMMULATORS	26	35
TRAPPED PROP.-FEED, FILL & DRAIN	660	680
TURBOPUMP GG PROP.	23	31
TRAPPED GH_2	10	19
TRAPPED GO_2	9	11
HE IN FUEL ACCUMMULATORS	79	151
HE IN OXID. ACCUMMULATORS	5	6
APS RESIDUAL FLUIDS & GASES	(110)	(6)
TRAPPED REACTANT-TANKS	104	--
TRAPPED REACTANT-APU'S/LINES	6	6
OMS INFLIGHT LOSSES	(--)	(--)
PROP. FOR ENGINE START/STOP ( )		
INERT WEIGHT	10,455	9,267

(CONT'D)

Table 2-5. (Continued)

ITEM	REFERENCE DEDICATED SYSTEMS	REFERENCE INTEGRATED SYSTEMS
(CON'T)		
RESERVES	(805)	(599)
OMS - O_2 } MR=6:1	--	--
" - H_2	--	--
RCS - O_2 } MR=4:1	352	--
" - H_2	88	--
APS - O_2 } MR=1:1	182.5	--
" - H_2	182.5	--
OMS/RCS/APS - O_2 } RSS OF	--	396
" " " - H_2 ABOVE	--	203
NOMINAL PROPELLANT/REACTANT	(2,930)	(2,930)
OMS @MR=6:1	--	--
RCS @MR=4:1	2,200	2,200
APS @MR=1:1	730	730
TOTAL WEIGHT	14,190	12,796

Table 2-6. Weight Scaling Equations for Integrated O_2/H_2 Subsystems (SSTO and HLLV)

<u>OMS DRY WEIGHT AND RESIDUAL WEIGHT</u> (SSTO AND HLLV ORBITER)

SSTO:

$$W_{DRY} = 0.022W_p + 1.57W_p^{2/3} + 0.034T + 1.4T^{1/2}$$

$$W_{RESIDUALS} = 0.0081W_p + 0.017T \quad \text{(INCL. LOSSES FOR 5 FIRINGS)}$$

HLLV ORBITER:

$$W_{DRY} = 0.022W_p + 1.57W_p^{2/3} + 0.034T + 2.1T^{1/2}$$

$$W_{RESIDUALS} = 0.0081W_p + 0.019T \quad \text{(INCL. LOSSES FOR 3 FIRINGS)}$$

WHERE

$$W_p = W_{p_{NOM.\ OMS}} + W_{p_{NOM.\ RCS}} + W_{p_{NOM.\ APS}} + W_{p_{RSS\ RESERVES}}$$

$$T = (TVAC_{OMS})\ \text{TOTAL INSTALLED}$$

SUBJECT TO

$$W_{p_{NOM.\ RCS}} \approx 9\% \rightarrow 18\%\ W_{p_{NOM.\ OMS}}$$

$$W_{p_{NOM.\ APS}} \approx 1.5\% \rightarrow 2.0\%\ W_{p_{NOM.\ OMS}}$$

<u>RCS DRY WEIGHT AND RESIDUALS WEIGHT</u> (SSTO AND HLLV ORBITER)

SSTO:

$$W_{DRY} = 0.059W_p + 1.9W_p^{2/3} + 0.020T + 3.3T^{1/2}$$

$$W_{RESIDUALS} = 0.035W_p + 0.0074T$$

HLLV ORBITER:

$$W_{DRY} = 0.059W_p + 1.9W_p^{2/3} + 0.020T + 3.3T^{1/2}$$

$$W_{RESIDUALS} = 0.035W_p + 0.0066T$$

WHERE

$$W_p = W_{p_{NOM.\ RCS}} + W_{p_{NOM.\ APS}}$$

$$T = (TVAC_{RCS})\ \text{TOTAL INSTALLED}$$

SUBJECT TO

$$W_{p_{NOM.\ APS}} \approx 10\% \rightarrow 18\%\ W_{p_{NOM.\ RCS}}$$

(CONT'D)

Table 2-6. (Continued)

RCS DRY WEIGHT AND RESIDUALS WEIGHT (HLLV BOOSTER)

$$W_{DRY} = 0.14W_p + 6.0W_p^{2/3} + 0.019T + 3.0T^{1/2}$$

$$W_{RESIDUALS} = 0.072W_p + 0.0057T$$

WHERE

$$W_p = W_{p_{NOM.\ RCS}} + W_{p_{NOM.\ APS}} + W_{p_{RSS\ RESERVES}}$$

$$T = (TVAC_{RCS})_{TOTAL\ INSTALLED}$$

SUBJECT TO

$$W_{p_{NOM.\ APS}} \approx 30\% \rightarrow 36\% W_{p_{NOM.\ RCS}}$$

APS DRY WEIGHT AND RESIDUALS WEIGHT $\begin{pmatrix} \text{SSTO} \\ \text{HLLV ORBITER} \\ \text{HLLV BOOSTER} \end{pmatrix}$

$$W_{DRY} = 1.4P_{MAX} + 5.4P_{MAX}^{1/2} + 280$$

$$W_{RESIDUALS} = 0.004P_{MAX}$$

WHERE

$$P_{MAX} = \left(P_{MAX.\ APS} \sim HP\right)_{TOTAL\ INSTALLED}$$

3.0 POTV VEHICLE

Simplified schematics of dedicated O_2/H_2 MPS/RCS/EPS subsystems are presented in figures 3-1, 3-2, and 3-3, respectively. A simplified schematic of integrated O_2/H_2 MPS/RCS/EPS subsystems is presented in figure 3-4. The updated fuel cell power requirements, power rating, and reactant weight previously referred to are presented in table 3-1. Primary weight estimating criteria for the O_2/H_2 subsystems is presented in table 3-2. A detailed weight comparison of dedicated and integrated O_2/H_2 MPS/RCS/EPS subsystems is presented in table 3-3.

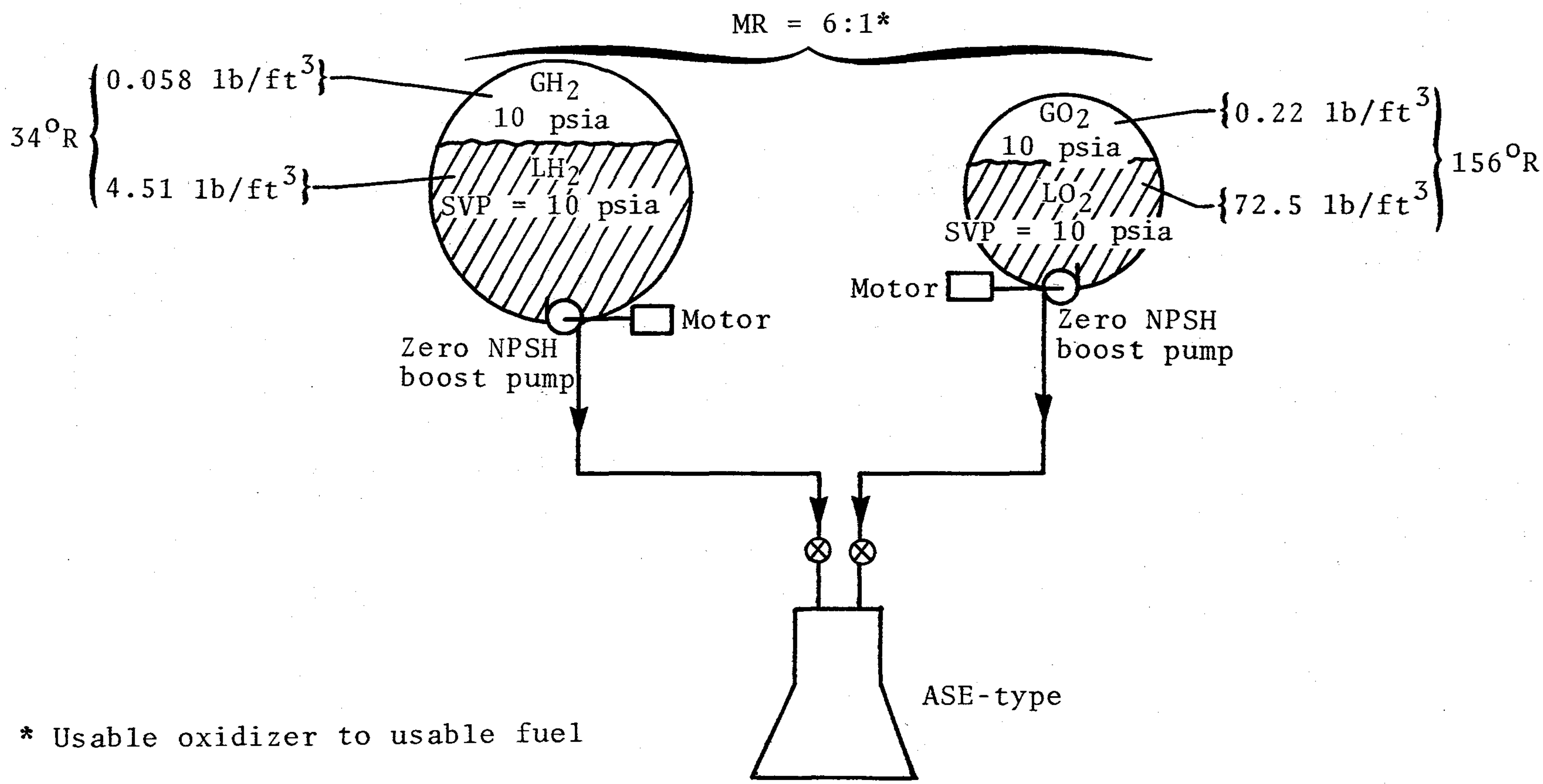
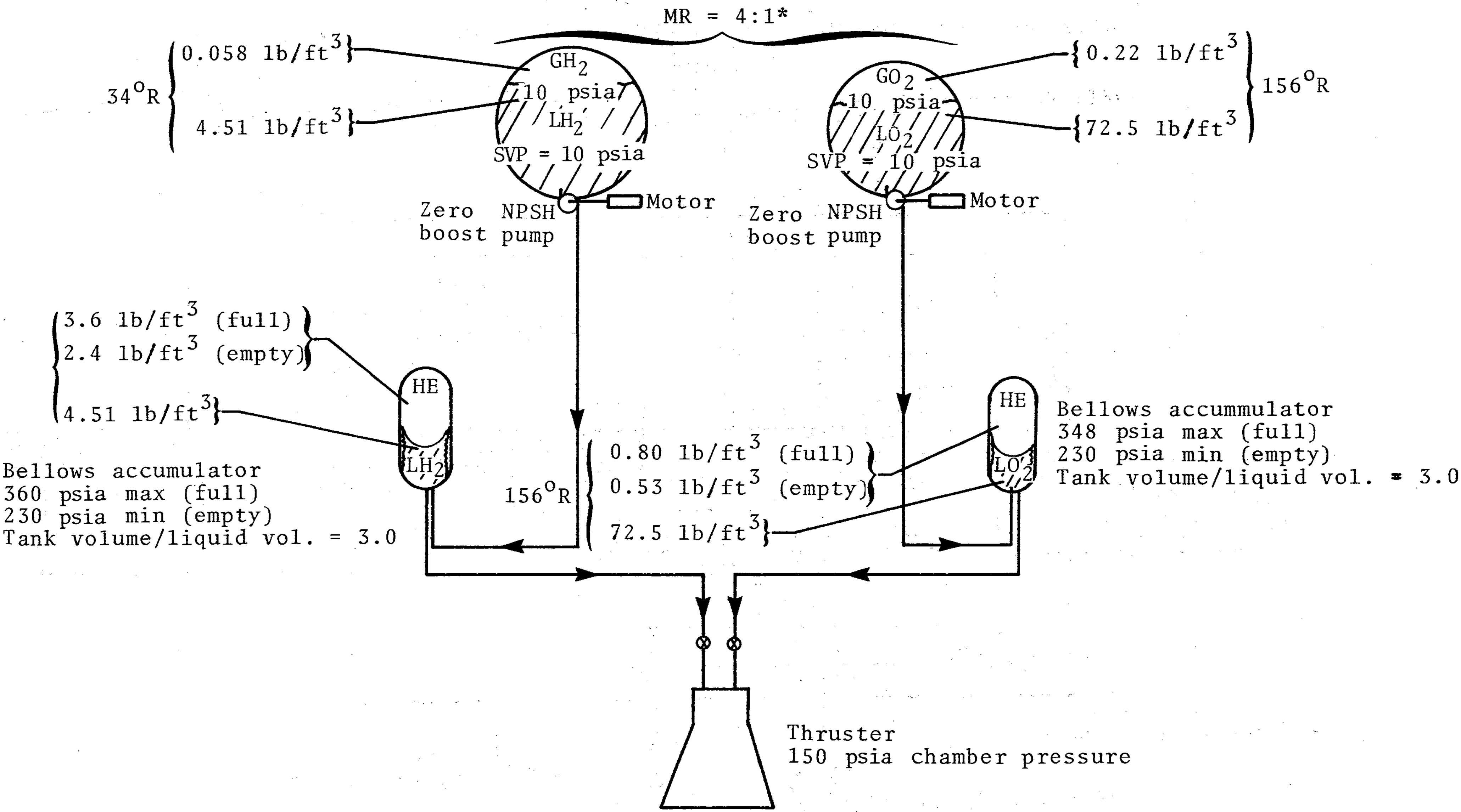
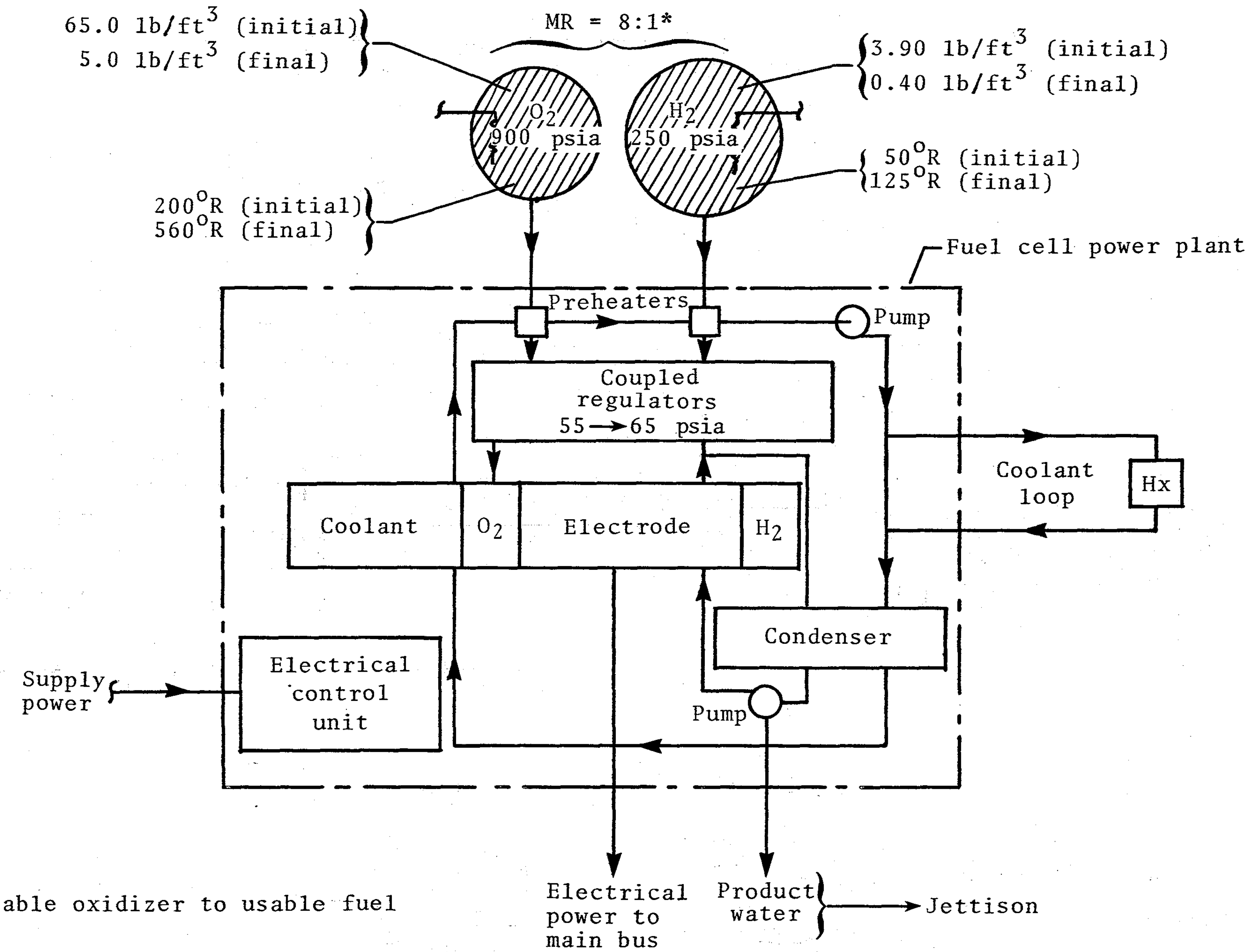


Figure 3-1. Simplified Schematic of LO_2/LH_2MPS POTV



* Usable oxidizer to usable fuel

Figure 3-2. Simplified Schematic of LO_2/LH_2 RCS POTV
Pumped Hydrogen/pumped oxygen



* Usable oxidizer to usable fuel

Figure 3-3. Simplified Schematic of O_2/H_2 Ruel Cell EPS POTV Supercritical Storage of O_2/H_2

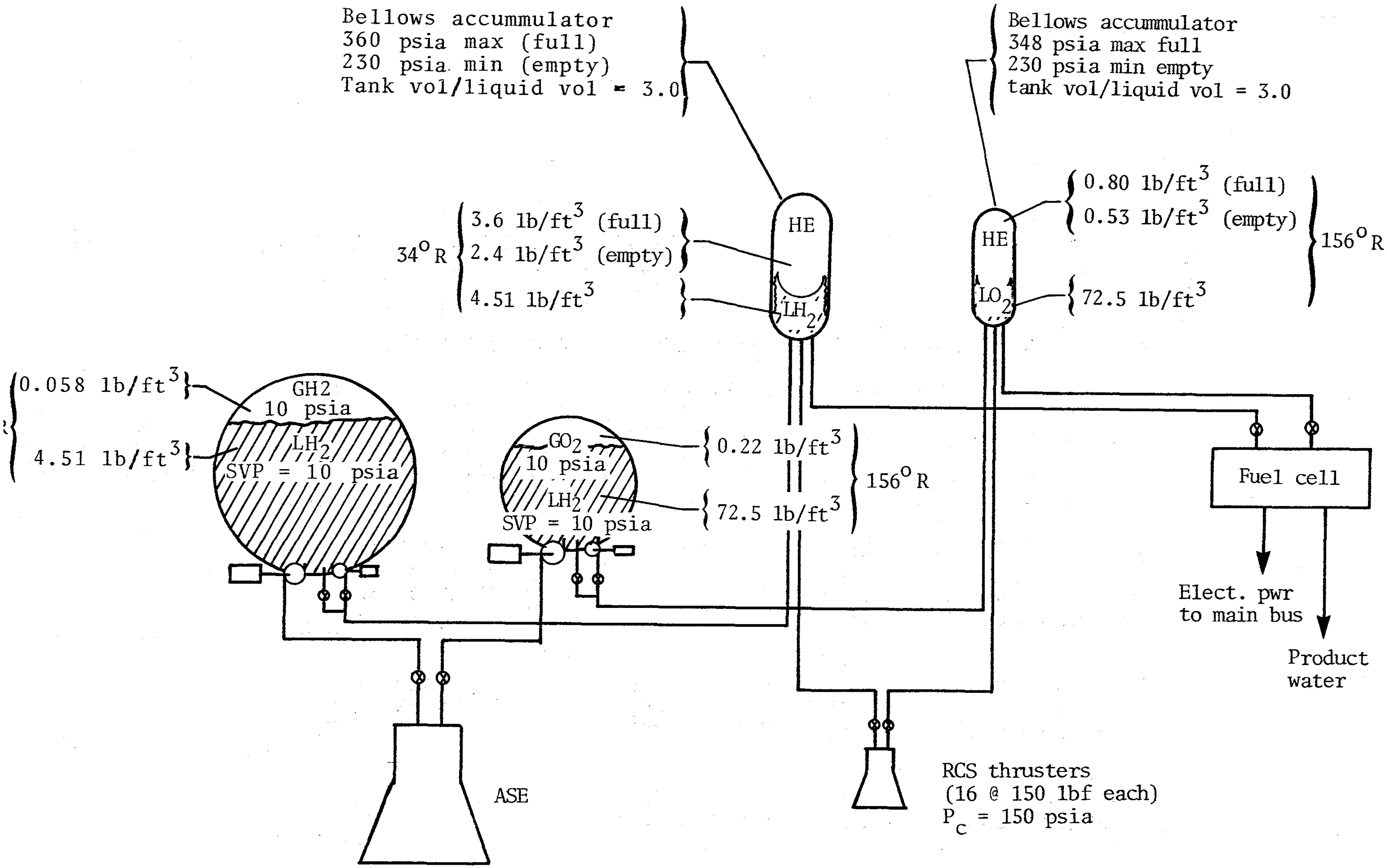


Figure 3-4. Simplified Schematic of Integrated LO_2/LH_2MPS/RCS/Fuel Cell EPS POTV

Table 3-1. Power Requirements/Fuel Cell Rating/Reactant Weight POTV (Normal Growth)

AVIONICS:								
BASIC	434	WATTS	x	73	HR	=	31,682	WATT-HR
RENDEZVOUS/DOCKING [1]	42	"	x	6	"	=	252	" "
MPS:								
BASIC	100	WATTS	x	73	HR	=	7,300	WATT-HR
MAIN ENGINES TVC	200	"	x	0.58	"	=	116	" "
BOOST PUMPS	620	"	x	0.58	"	=	360	" "
APS/RCS:								
BASIC	50	WATTS	x	73	HR	=	3,650	WATT-HR
ACCUM. CHARGING [2]	530	"	x	5	"	=	2,650	" "
EPS & DISTRIBUTION:	100	WATTS	x	73	HR	=	7,300	WATT-HR
PAYLOAD:	----------						----------	

POWER REQUIREMENTS: 2,076 WATTS 53,310 WATT-HR

FUEL CELL RATING: 1.3 KW WITH 2.1 KW PEAK

REACTANT WEIGHT @ 1,228 WATT-HR/LB = 33% RESERVE = 58 LB

[1] REFLECTS ACTUATION OF RADAR/TV

[2] REFLECTS THRUST P_c = 150 PSIA

Table 3-2. Primary Weight Estimating Criteria for Dedicated/Integrated O_2/H_2 Subsystems 1 (POTV)

ENGINES (MPS):
- ASE-TYPE @20,000 LB TVAC EACH
- NPSH OF LO-PRESS FUEL PUMP = 0.5 PSI
- NPSH OF LO-PRESS OXID. PUMP = 1.0 PSI

THRUSTERS (RCS):
- 16 @150 LB TVAC EACH

FULL CELLS (EPS):
- 2 O_2/H_2 UNITS
- UNINSTALLED WEIGHT = 35 LB/KW(AVE)

BACK-UP BATTERY (EPS):
- POWER REQUIREMENT: 13 AMP-HR, 28V
- Ni - H_2 @25 WATT-HR/LB

BOOST PUMPS/MOTORS (MPS,RCS):
- ZERO NPSH BOOST PUMPS
- ELECTRIC MOTORS
- REDUNDANCY:
  - MPS - NONE $\left\{\begin{array}{l}\text{3 FUEL, 2 REQ'D}\\ \text{3 OXID., 2 REQ'D}\end{array}\right\}$
  - EPS - 6 SETS

PROPELLANT TANKS (MPS, RCS, EPS):
- SPHERICAL
- 2219-T87
- 50 MISSION SERVICE LIFE REQUIREMENT

BELLOWS ACCUMMULATORS (RCS):
- CYLINDRICAL
- 2219-T87 PRESSURE SHELL
- STAINLESS STEEL BELLOWS
- 50 MISSION SERVICE LIFE REQUIREMENT
- NO. OF ACCUMMULATORS: 2 FUEL, 2 OXID.
- TOTAL ACCUMMULATOR CAPACITY:

$\left.\begin{array}{l}\text{17\% USABLE RCS PROP. (DEDICATED)}\\ \text{17\% USABLE RCS/EPS PROP. (INTEGRATED)}\end{array}\right\}$ GEO DOCKING

(CONT'D)

1 SEE SIMPLIFIED SCHEMATICS AND FULL CELL POWER ESTIMATES FOR ADDITIONAL DATA.

Table 3-2. (Continued)

PRESSURE SHELL PROOF FACTORS (MPS,RCS,EPS):

	MPS	RCS		EPS
		TANKS	ACCUM'S	
SERVICE LIFE REQ'T-MISSIONS	50	50	50	50
PRESSURE CYCLING-PER MISSION				
FUEL DEPTH	0	0	0	0
PARTIAL	6	0	6	0
EQUIV. FULL DEPTH	0.40	0	0.66	50
PRESSURE CYCLING-OPER. CONTINGENCY				
FULL DEPTH	5	5	5	5
DESIGN CYCLES (FULL DEPTH)	50	10	76	110
STRESS INTENSITY RATIO				
LOWER BOUNDARY CURVE	0.68	0.77	0.65	0.62
PROOF FACTOR	1.48	1.27	1.54	1.61

THERMAL CONTROL (MPS,EPS)

MLI BLANKET ENCLOSING EACH MAIN TANK, AND SPACECRAFT FRAME

RADIATOR SYSTEM FOR FUEL CELLS

Table 3-3. Detail Weight Comparison of Integrated vs Dedicated O_2/H_2 MPS/RCS/EPS POTV

(All Weights in Pounds)

ITEM	REFERENCE DEDICATED SYSTEMS	REFERENCE INTEGRATED SYSTEMS
MPS (PLUS ASSOC.STRUCT.AND THERMAL CONTROL)	(4,670)	(4,693)
MAIN ENGINES & ACCESSORIES (2)	910	910
ZERO NPSH BOOST PUMPS/MOTORS (2 SETS)	80	80
PROPELLANT FEED, FILL & DRAIN	200	200
VENT/RELIEF	250	250
PNEUMATIC	145	145
PROPELLANT LOADING/MONITORING	75	75
FUEL TANK	1,014	1,023
OXIDIZER TANK	772	777
PRIMARY TRUSSES	170	174
THRUST STRUCTURE	85	85
FUEL TANK INSULATION	268	270
OXIDIZER TANK INSULATION	139	140
SPACECRAFT INSULATION	502	504
BASE HEAT SHIELD	60	60
RCS	(945)	(857)
FUEL TANK	42	--
OXIDIZER TANK	15	--
ZERO NPSH PUMPS/MOTORS (6 SETS)	14	14
FEED LINES	40	50
COMPENSATORS	10	10
FUEL BELLOWS ACCUMMULATORS (2)	376	378
OXIDIZER BELLOWS ACCUMMULATORS (2)	96	97
ISOLATION VALVES	40	40
PRESSURIZATION-VENT/RELIEF	40	20
THRUSTERS-INCLUDING VALVES (16-150 LBF)	141	141
INSULATION	45	29
SUPPORTS/INSTALLATION	86	78
EPS (PLUS ASSOC. PWR. PROCESS. & DISTR. AND THERM. CONTR)	(351)	(308)
FUEL CELLS (2)	90	90
BATTERY	15	15
HYDROGEN TANK	6	--
OXYGEN TANK	10	--
REACTANT FEED SYSTEM	15	15
PRESSURIZATION-TANK VENT/RELIEF	20	--
INSULATION/INTERNAL HEATERS-TANKS	3	--
SUPPORTS/INSTALLATION	16	12
POWER PROCESSING & DISTRIBUTION	120	120
FUEL CELL THERMAL CONTROL	56	56
DRY WEIGHT - LESS MARGIN	5,966	5,858

(CONT'D)

Table 3-3. (Continued)

(ALL WEIGHTS IN POUNDS)

ITEMS	REFERENCE DEDICATED SYSTEMS	REFERENCE INTEGRATED SYSTEMS
(CON'T)		
MARGIN	(597)	(586)
DRY WEIGHT	6,563	6,444
MPS RESIDUAL FLUIDS & GASES	(1,780)	(1,787)
TRAPPED LH_2	80	80
TRAPPED LO_2	480	480
LH_2 BIAS	151	151
TRAPPED GH_2	475	478
TRAPPED GO_2	595	598
RCS RESIDUAL FLUIDS & GASES	(156)	(139)
TRAPPED LH_2 - TANK	5	--
" " - PUMPS		
" " - ACCUMMULATORS	5	5
" " - LINES	1	2
TRAPPED LO_2 - TANK	19	--
" " - PUMPS	3	3
" " - ACCUMMULATORS	19	19
" " - LINES	17	29
TRAPPED GH_2	3	--
TRAPPED GO_2	3	--
HE IN FUEL ACCUMMULATOR	77	77
HE IN OXIDIZER ACCUMMULATOR	4	4
EPS RESIDUAL FLUIDS & GASES	(5)	(2)
TRAPPED O_2 - TANK	4	--
TRAPPED H_2 - TANK	0.7	--
TRAPPED O_2 & H_2 - FUEL CELLS/LINES	0.3	2
(CONT'D)		

Table 3-3. (Continued)

(ALL WEIGHTS IN POUNDS)

ITEM	REFERENCE DEDICATED SYSTEMS	REFERENCE INTEGRATED SYSTEMS
(CONT'D)		
MPS INFLIGHT LOSSES	(522)	(524)
H_2 BOILOFF	116	117
O_2 BOILOFF	106	107
LH_2 FOR ENGINE START/STOP (6)	60	60
LO_2 FOR ENGINE START/STOP (6)	240	240
INERT WEIGHT	9,026	8,896
RESERVES	(1,254)	(1,118)
MPS - O_2 MR=6:1	951	--
" - H_2 MR=6:1	159	--
RCS - O_2 MR=4:1	104	--
" - H_2 MR=4:1	26	--
EPS - O_2 MR=8:1	12.5	--
" - H_2 MR=8:1	1.5	--
MPS/RCS/EPS - O_2 R.S.S.	--	957
" " " - H_2 R.S.S.	--	161
NOMINAL PROPELLANT/REACTANT	(174,514)	(174,514)
MPS @MR=6:1	173,160	173,160
RCS @MR=4:1	1,310	1,310
EPS @MR=8:1	44	44
TOTAL WEIGHT	184,794	184,528

APPENDIX E

CONVERSION FACTORS

CONVERSION FACTORS

The following tables express the definitions of miscellaneous units of measure as exact numerical multiples of coherent SI units, and provide multiplying factors for converting numbers and miscellaneous units to corresponding new numbers and SI units.

The first two digits of each numerical entry represent a power of 10. An asterisk follows each number which expresses an exact definition. For example, the entry "−02 2.54*" expresses the fact that 1 inch$=2.54\times10^{-2}$ meter, exactly, by definition. Most of the definitions are extracted from National Bureau of Standards documents. Numbers not followed by an asterisk are only approximate representations of definitions, or are the results of physical measurements.

The conversion factors are listed alphabetically and by physical quantity.

The Listing by Physical Quantity includes only relationships which are frequently encountered and deliberately omits the great multiplicity of combinations of units which are used for more specialized purposes. Conversion factors for combinations of units are easily generated from numbers given in the Alphabetical Listing by the technique of direct substitution or by other well-known rules for manipulating units. These rules are adequately discussed in many science and engineering textbooks and are not repeated here.

ALPHABETICAL LISTING

To convert from	*to*	*multiply by*
abampere	ampere	+01 1.00*
abcoulomb	coulomb	+01 1.00*
abfarad	farad	+09 1.00*
abhenry	henry	−09 1.00*
abmho	siemens	+09 1.00*
abohm	ohm	−09 1.00*
abvolt	volt	−08 1.00*
acre	meter^2	+03 4.046 856 422 4*
angstrom	meter	−10 1.00*
are	meter^2	+02 1.00*
astronomical unit (IAU)	meter	+11 1.496 00
astronomical unit (radio)	meter	+11 1.495 978 9
atmosphere	newton/meter^2	+05 1.013 25*
bar	newton/meter^2	+05 1.00*
barn	meter^2	−28 1.00*
barrel (petroleum, 42 gallons)	meter^3	−01 1.589 873
barye	newton/meter^2	−01 1.00*
board foot (1′×1′×1″)	meter^3	−03 2.359 737 216*
British thermal unit:		
(IST before 1956)	joule	+03 1.055 04
(IST after 1956)	joule	+03 1.055 056
British thermal unit (mean)	joule	+03 1.055 87
British thermal unit (thermochemical)	joule	+03 1.054 350
British thermal unit (39° F)	joule	+03 1.059 67
British thermal unit (60° F)	joule	+03 1.054 68
bushel (U.S.)	meter^3	−02 3.523 907 016 688*
cable	meter	+02 2.194 56*
caliber	meter	−04 2.54*
calorie (International Steam Table)	joule	+00 4.1868
calorie (mean)	joule	+00 4.190 02
calorie (thermochemical)	joule	+00 4.184*
calorie (15° C)	joule	+00 4.185 80

To convert from	*to*	*multiply by*
calorie (20° C)	joule	+00 4.181 90
calorie (kilogram, International Steam Table)	joule	+03 4.1868
calorie (kilogram, mean)	joule	+03 4.190 02
calorie (kilogram, thermochemical)	joule	+03 4.184*
carat (metric)	kilogram	−04 2.00*
Celsius (temperature)	kelvin	$t_K = t_C + 273.15$
centimeter of mercury (0° C)	newton/meter^2	+03 1.333 22
centimeter of water (4° C)	newton/meter^2	+01 9.806 38
chain (engineer or ramden)	meter	+01 3.048*
chain (surveyor or gunter)	meter	+01 2.011 68*
circular mil	meter^2	−10 5.067 074 8
cord	meter^3	+00 3.624 556 3
cubit	meter	−01 4.572*
cup	meter^3	−04 2.365 882 365*
curie	disintegration/second	+10 3.70*
day (mean solar)	second (mean solar)	+04 8.64*
day (sidereal)	second (mean solar)	+04 8.616 409 0
degree (angle)	radian	−02 1.745 329 251 994 3
denier (international)	kilogram/meter	−07 1.00*
dram (avoirdupois)	kilogram	−03 1.771 845 195 312 5*
dram (troy or apothecary)	kilogram	−03 3.887 934 6*
dram (U.S. fluid)	meter^3	−06 3.696 691 195 312 5*
dyne	newton	−05 1.00*
electron volt	joule	−19 1.602 191 7
erg	joule	−07 1.00*
Fahrenheit (temperature)	kelvin	$t_K = (5/9)\ (t_F + 459.67)$
Fahrenheit (temperature)	Celsius	$t_C = (5/9)\ (t_F - 32)$
faraday (based on carbon 12)	coulomb	+04 9.648 70
faraday (chemical)	coulomb	+04 9.649 57
faraday (physical)	coulomb	+04 9.652 19
fathom	meter	+00 1.828 8*
fermi (femtometer)	meter	−15 1.00*
fluid ounce (U.S.)	meter^3	−05 2.957 352 956 25*
foot	meter	−01 3.048*
foot (U.S. survey)	meter	+00 1200/3937*
foot (U.S. survey)	meter	−01 3.048 006 096
foot of water (39.2° F)	newton/meter^2	+03 2.988 98
footcandle	lumen/meter^2	+01 1.076 391 0
footlambert	candela/meter^2	+00 3.426 259
free fall, standard	meter/second^2	+00 9.806 65*
furlong	meter	+02 2.011 68*
gal (galileo)	meter/second^2	−02 1.00*
gallon (U.K. liquid)	meter^3	−03 4.546 087
gallon (U.S. dry)	meter^3	−03 4.404 883 770 86*
gallon (U.S. liquid)	meter^3	−03 3.785 411 784*
gamma	tesla	−09 1.00*
gauss	tesla	−04 1.00*
gilbert	ampere turn	−01 7.957 747 2
gill (U.K.)	meter^3	−04 1.420 652
gill (U.S.)	meter^3	−04 1.182 941 2
grad	degree (angular)	−01 9.00*
grad	radian	−02 1.570 796 3
grain	kilogram	−05 6.479 891*
gram	kilogram	−03 1.00*

To convert from	*to*	*multiply by*
hand	meter	−01 1.016*
hectare	$meter^2$	+04 1.00*
hogshead (U.S.)	$meter^3$	−01 2.384 809 423 92*
horsepower (550 foot lbf/second)	watt	+02 7.456 998 7
horsepower (boiler)	watt	+03 9.809 50
horsepower (electric)	watt	+02 7.46*
horsepower (metric)	watt	+02 7.354 99
horsepower (U.K.)	watt	+02 7.457
horsepower (water)	watt	+02 7.460 43
hour (mean solar)	second (mean solar)	+03 3.60*
hour (sidereal)	second (mean solar)	+03 3.590 170 4
hundredweight (long)	kilogram	+01 5.080 234 544*
hundredweight (short)	kilogram	+01 4.535 923 7*
inch	meter	−02 2.54*
inch of mercury (32° F)	newton/$meter^2$	+03 3.386 389
inch of mercury (60° F)	newton/$meter^2$	+03 3.376 85
inch of water (39.2° F)	newton/$meter^2$	+02 2.490 82
inch of water (60° F)	newton/$meter^2$	+02 2.4884
kayser	1/meter	+02 1.00*
kilocalorie (International Steam Table)	joule	+03 4.186 8
kilocalorie (mean)	joule	+03 4.190 02
kilocalorie (thermochemical)	joule	+03 4.184*
kilogram mass	kilogram	+00 1.00*
kilogram force (kgf)	newton	+00 9.806 65*
kilopound force	newton	+00 9.806 65*
kip	newton	+03 4.448 221 615 260 5*
knot (international)	meter/second	−01 5.144 444 444
lambert	candela/$meter^2$	+04 $1/\pi$*
lambert	candela/$meter^2$	+03 3.183 098 8
langley	joule/$meter^2$	+04 4.184*
lbf (pound force, avoirdupois)	newton	+00 4.448 221 615 260 5*
lbm (pound mass, avoirdupois)	kilogram	−01 4.535 923 7*
league (U.K. nautical)	meter	+03 5.559 552*
league (international nautical)	meter	+03 5.556*
league (statute)	meter	+03 4.828 032*
light year	meter	+15 9.460 55
link (engineer or ramden)	meter	−01 3.048*
link (surveyor or gunter)	meter	−01 2.011 68*
liter	$meter^3$	−03 1.00*
lux	lumen/$meter^2$	+00 1.00*
maxwell	weber	−08 1.00*
meter	wavelengths Kr 86	+06 1.650 763 73*
micron	meter	−06 1.00*
mil	meter	−05 2.54*
mile (U.S. statute)	meter	+03 1.609 344*
mile (U.K. nautical)	meter	+03 1.853 184*
mile (international nautical)	meter	+03 1.852*
mile (U.S. nautical)	meter	+03 1.852*
millibar	newton/$meter^2$	+02 1.00*
millimeter of mercury (0° C)	newton/$meter^2$	+02 1.333 224
minute (angle)	radian	−04 2.908 882 086 66
minute (mean solar)	second (mean solar)	+01 6.00*
minute (sidereal)	second (mean solar)	+01 5.983 617 4
month (mean calendar)	second (mean solar)	+06 2.628*

To convert from	*to*	*multiply by*
nautical mile (international)	meter	+03 1.852*
nautical mile (U.S.)	meter	+03 1.852*
nautical mile (U.K.)	meter	+03 1.853 184*
oersted	ampere/meter	+01 7.957 747 2
ounce force (avoirdupois)	newton	−01 2.780 138 5
ounce mass (avoirdupois)	kilogram	−02 2.834 952 312 5*
ounce mass (troy or apothecary)	kilogram	−02 3.110 347 68*
ounce (U.S. fluid)	meter^3	−05 2.957 352 956 25*
pace	meter	−01 7.62*
parsec (IAU)	meter	+16 3.085 7
pascal	newton/meter^2	+00 1.00*
peck (U.S.)	meter^3	−03 8.809 767 541 72*
pennyweight	kilogram	−03 1.555 173 84*
perch	meter	+00 5.0292*
phot	lumen/meter^2	+04 1.00
pica (printers)	meter	−03 4.217 517 6*
pint (U.S. dry)	meter^3	−04 5.506 104 713 575*
pint (U.S. liquid)	meter^3	−04 4.731 764 73*
point (printers)	meter	−04 3.514 598*
poise	newton second/meter^2	−01 1.00*
pole	meter	+00 5.0292*
pound force (lbf avoirdupois)	newton	+00 4.448 221 615 260 5*
pound mass (lbm avoirdupois)	kilogram	−01 4.535 923 7*
pound mass (troy or apothecary)	kilogram	−01 3.732 417 216*
poundal	newton	−01 1.382 549 543 76*
quart (U.S. dry)	meter^3	−03 1.101 220 942 715*
quart (U.S. liquid)	meter^3	−04 9.463 592 5
rad (radiation dose absorbed)	joule/kilogram	−02 1.00*
Rankine (temperature)	kelvin	$t_K = (5/9)t_R$
rayleigh (rate of photon emission)	1/second meter^2	+10 1.00*
rhe	meter^2/newton second	+01 1.00*
rod	meter	+00 5.0292*
roentgen	coulomb/kilogram	−04 2.579 76*
rutherford	disintegration/second	+06 1.00*
second (angle)	radian	−06 4.848 136 811
second (ephemeris)	second	+00 1.000 000 000
second (mean solar)	second (ephemeris)	Consult American Ephemeris and Nautical Almanac
second (sidereal)	second (mean solar)	−01 9.972 695 7
section	meter^2	+06 2.589 988 110 336*
scruple (apothecary)	kilogram	−03 1.295 978 2*
shake	second	−08 1.00
skein	meter	+02 1.097 28*
slug	kilogram	+01 1.459 390 29
span	meter	−01 2.286*
statampere	ampere	−10 3.335 640
statcoulomb	coulomb	−10 3.335 640
statfarad	farad	−12 1.112 650
stathenry	henry	+11 8.987 554
statohm	ohm	+11 8.987 554
statute mile (U.S.)	meter	+03 1.609 344*
statvolt	volt	+02 2.997 925
stere	meter^3	+00 1.00*

To convert from	*to*	*multiply by*
stilb	candela/meter^2	+04 1.00
stoke	meter^2/second	−04 1.00*
tablespoon	meter^3	−05 1.478 676 478 125*
teaspoon	meter^3	−06 4.928 921 593 75*
ton (assay)	kilogram	−02 2.916 666 6
ton (long)	kilogram	+03 1.016 046 908 8*
ton (metric)	kilogram	+03 1.00*
ton (nuclear equivalent of TNT)	joule	+09 4.20
ton (register)	meter^3	+00 2.831 684 659 2*
ton (short, 2000 pound)	kilogram	+02 9.071 847 4*
tonne	kilogram	+03 1.00*
torr (0° C)	newton/meter^2	+02 1.333 22
township	meter^2	+07 9.323 957 2
unit pole	weber	−07 1.256 637
yard	meter	−01 9.144*
year (calendar)	second (mean solar)	+07 3.1536*
year (sidereal)	second (mean solar)	+07 3.155 815 0
year (tropical)	second (mean solar)	+07 3.155 692 6
year 1900, tropical, Jan., day 0, hour 12	second (ephemeris)	+07 3.155 692 597 47*
year 1900, tropical, Jan., day 0, hour 12	second	+07 3.155 692 597 47

LISTING BY PHYSICAL QUANTITY

ACCELERATION

foot/second^2	meter/second^2	−01 3.048*
free fall, standard	meter/second^2	+00 9.806 65*
gal (galileo)	meter/second^2	−02 1.00*
inch/second^2	meter/second^2	−02 2.54*

AREA

acre	meter^2	+03 4.046 856 422 4*
are	meter^2	+02 1.00*
barn	meter^2	−28 1.00*
circular mil	meter^2	−10 5.067 074 8
foot^2	meter^2	−02 9.290 304*
hectare	meter^2	+04 1.00*
inch^2	meter^2	−04 6.4516*
mile^2 (U.S. statute)	meter^2	+06 2.589 988 110 336*
section	meter^2	+06 2.589 988 110 336*
township	meter^2	+07 9.323 957 2
yard^2	meter^2	−01 8.361 273 6*

DENSITY

gram/centimeter^3	kilogram/meter^3	+03 1.00*
lbm/inch^3	kilogram/meter^3	+04 2.767 990 5
lbm/foot^3	kilogram/meter^3	+01 1.601 846 3
slug/foot^3	kilogram/meter^3	+02 5.153 79

To convert from	*to*	*multiply by*

ENERGY

British thermal unit:		
(IST before 1956)	joule	+03 1.055 04
(IST after 1956)	joule	+03 1.055 056
British thermal unit (mean)	joule	+03 1.055 87
British thermal unit (thermochemical)	joule	+03 1.054 350
British thermal unit (39° F)	joule	+03 1.059 67
British thermal unit (60° F)	joule	+03 1.054 68
calorie (International Steam Table)	joule	+00 4.1868
calorie (mean)	joule	+00 4.190 02
calorie (thermochemical)	joule	+00 4.184*
calorie (15° C)	joule	+00 4.185 80
calorie (20° C)	joule	+00 4.181 90
calorie (kilogram, International Steam Table)	joule	+03 4.1868
calorie (kilogram, mean)	joule	+03 4.190 02
calorie (kilogram, thermochemical)	joule	+03 4.184*
electron volt	joule	−19 1.602 191 7
erg	joule	−07 1.00*
foot lbf	joule	+00 1.355 817 9
foot poundal	joule	−02 4.214 011 0
joule (international of 1948)	joule	+00 1.000 165
kilocalorie (International Steam Table)	joule	+03 4.1868
kilocalorie (mean)	joule	+03 4.190 02
kilocalorie (thermochemical)	joule	+03 4.184*
kilowatt hour	joule	+06 3.60*
kilowatt hour (international of 1948)	joule	+06 3.600 59
ton (nuclear equivalent of TNT)	joule	+09 4.20
watt hour	joule	+03 3.60*

ENERGY/AREA TIME

Btu (thermochemical)/foot^2 second	watt/meter^2	+04 1.134 893 1
Btu (thermochemical)/foot^2 minute	watt/meter^2	+02 1.891 488 5
Btu (thermochemical)/foot^2 hour	watt/meter^2	+00 3.152 480 8
Btu (thermochemical)/inch^2 second	watt/meter^2	+06 1.634 246 2
calorie (thermochemical)/cm^2 minute	watt/meter^2	+02 6.973 333 3
erg/centimeter^2 second	watt/meter^2	−03 1.00*
watt/centimeter^2	watt/meter^2	+04 1.00*

FORCE

dyne	newton	−05 1.00*
kilogram force (kgf)	newton	+00 9.806 65*
kilopond force	newton	+00 9.806 65*
kip	newton	+03 4.448 221 615 260 5*
lbf (pound force, avoirdupois)	newton	+00 4.448 221 615 260 5*
ounce force (avoirdupois)	newton	−01 2.780 138 5
pound force, lbf (avoirdupois)	newton	+00 4.448 221 615 260 5*
poundal	newton	−01 1.382 549 543 76*

LENGTH

angstrom	meter	−10 1.00*
astronomical unit (IAU)	meter	+11 1.496 00
astronomical unit (radio)	meter	+11 1.495 978 9
cable	meter	+02 2.194 56*

To convert from	*to*	*multiply by*
caliber	meter	−04 2.54*
chain (surveyor or gunter)	meter	+01 2.011 68*
chain (engineer or ramden)	meter	+01 3.048*
cubit	meter	−01 4.572*
fathom	meter	+00 1.8288*
fermi (femtometer)	meter	−15 1.00*
foot	meter	−01 3.048*
foot (U.S. survey)	meter	+00 1200/3937*
foot (U.S. survey)	meter	−01 3.048 006 096
furlong	meter	+02 2.011 68*
hand	meter	−01 1.016*
inch	meter	−02 2.54*
league (U.K. nautical)	meter	+03 5.559 552*
league (international nautical)	meter	+03 5.556*
league (statute)	meter	+03 4.828 032*
light year	meter	+15 9.460 55
link (engineer or ramden)	meter	−01 3.048*
link (surveyor or gunter)	meter	−01 2.011 68*
meter	wavelengths Kr 86	+06 1.650 763 73*
micron	meter	−06 1.00*
mil	meter	−05 2.54*
mile (U.S. statute)	meter	+03 1.609 344*
mile (U.K. nautical)	meter	+03 1.853 184*
mile (international nautical)	meter	+03 1.852*
mile (U.S. nautical)	meter	+03 1.852*
nautical mile (U.K.)	meter	+03 1.853 184*
nautical mile (international)	meter	+03 1.852*
nautical mile (U.S.)	meter	+03 1.852*
pace	meter	−01 7.62*
parsec (IAU)	meter	+16 3.085 7
perch	meter	+00 5.0292*
pica (printers)	meter	−03 4.217 517 6*
point (printers)	meter	−04 3.514 598*
pole	meter	+00 5.0292*
rod	meter	+00 5.0292*
skein	meter	+02 1.097 28*
span	meter	−01 2.286*
statute mile (U.S.)	meter	+03 1.609 344*
yard	meter	−01 9.144*

MASS

carat (metric)	kilogram	−04 2.00*
gram (avoirdupois)	kilogram	−03 1.771 845 195 312 5*
gram (troy or apothecary)	kilogram	−03 3.887 934 6*
grain	kilogram	−05 6.479 891*
gram	kilogram	−03 1.00*
hundredweight (long)	kilogram	+01 5.080 234 544*
hundredweight (short)	kilogram	+01 4.535 923 7*
kgf second^2 meter (mass)	kilogram	+00 9.806 65*
kilogram mass	kilogram	+00 1.00*
lbm (pound mass, avoirdupois)	kilogram	−01 4.535 923 7*
ounce mass (avoirdupois)	kilogram	−02 2.834 952 312 5*
ounce mass (troy or apothecary)	kilogram	−02 3.110 347 68*
pennyweight	kilogram	−03 1.555 173 84*
pound mass, lbm (avoirdupois)	kilogram	−01 4.535 923 7*

To convert from	*to*	*multiply by*
pound mass (troy or apothecary)	kilogram	−01 3.732 417 216*
scruple (apothecary)	kilogram	−03 1.295 978 2*
slug	kilogram	+01 1.459 390 29
ton (assay)	kilogram	−02 2.916 666 6
ton (long)	kilogram	+03 1.016 046 908 8*
ton (metric)	kilogram	+03 1.00*
ton (short, 2000 pound)	kilogram	+02 9.071 847 4*
tonne	kilogram	+03 1.00*

POWER

Btu (thermochemical)/second	watt	+03 1.054 350 264 488
Btu (thermochemical)/minute	watt	+01 1.757 250 4
calorie (thermochemical)/second	watt	+00 4.184*
calorie (thermochemical)/minute	watt	−02 6.973 333 3
foot lbf/hour	watt	−04 3.766 161 0
foot lbf/minute	watt	−02 2.259 696 6
foot lbf/second	watt	+00 1.355 817 9
horsepower (550 foot lbf/second)	watt	+02 7.456 998 7
horsepower (boiler)	watt	+03 9.809 50
horsepower (electric)	watt	+02 7.46*
horsepower (metric)	watt	+02 7.354 99
horsepower (U.K.)	watt	+02 7.457
horsepower (water)	watt	+02 7.460 43
kilocalorie (thermochemical)/minute	watt	+01 6.973 333 3
kilocalorie (thermochemical)/second	watt	+03 4.184*
watt (international of 1948)	watt	+00 1.000 165

PRESSURE

atmosphere	newton/meter^2	+05 1.013 25*
bar	newton/meter^2	+05 1.00*
barye	newton/meter^2	−01 1.00*
centimeter of mercury (0° C)	newton/meter^2	+03 1.333 22
centimeter of water (4° C)	newton/meter^2	+01 9.806 38
dyne/centimeter^2	newton/meter^2	−01 1.00*
foot of water (39.2° F)	newton/meter^2	+03 2.988 98
inch of mercury (32° F)	newton/meter^2	+03 3.386 389
inch of mercury (60° F)	newton/meter^2	+03 3.376 85
inch of water (39.2° F)	newton/meter^2	+02 2.490 82
inch of water (60° F)	newton/meter^2	+02 2.4884
kgf/centimeter^2	newton/meter^2	+04 9.806 65*
kgf/meter^2	newton/meter^2	+00 9.806 65*
lbf/foot^2	newton/meter^2	+01 4.788 025 8
lbf/inch^2 (psi)	newton/meter^2	+03 6.894 757 2
millibar	newton/meter^2	+02 1.00*
millimeter of mercury (0° C)	newton/meter^2	+02 1.333 224
pascal	newton/meter^2	+00 1.00*
psi (lbf/inch^2)	newton/meter^2	+03 6.894 757 2
torr (0° C)	newton/meter^2	+02 1.333 22

SPEED

foot/hour	meter/second	−05 8.466 666 6
foot/minute	meter/second	−03 5.08*
foot/second	meter/second	−01 3.048*
inch/second	meter/second	−02 2.54*

To convert from	*to*	*multiply by*
kilometer/hour	meter/second	−01 2.777 777 8
knot (international)	meter/second	−01 5.144 444 444
mile/hour (U.S. statute)	meter/second	−01 4.4704*
mile/minute (U.S. statute)	meter/second	+01 2.682 24*
mile/second (U.S. statute)	meter/second	+03 1.609 344*

TEMPERATURE

Celsius	kelvin	$t_K = t_C + 273.15$
Fahrenheit	kelvin	$t_K = (5/9)(t_F + 459.67)$
Fahrenheit	Celsius	$t_C = (5/9)(t_F - 32)$
Rankine	kelvin	$t_K = (5/9)t_R$

TIME

day (mean solar)	second (mean solar)	+04 8.64*
day (sidereal)	second (mean solar)	+04 8.616 409 0
hour (mean solar)	second (mean solar)	+03 3.60*
hour (sidereal)	second (mean solar)	+03 3.590 170 4
minute (mean solar)	second (mean solar)	+01 6.00*
minute (sidereal)	second (mean solar)	+01 5.983 617 4
month (mean calendar)	second (mean solar)	+06 2.628*
second (ephemeris)	second	+00 1.000 000 000
second (mean solar)	second (ephemeris)	Consult American Ephemeris and Nautical Almanac
second (sidereal)	second (mean solar)	−01 9.972 695 7
year (calendar)	second (mean solar)	+07 3.1536*
year (sidereal)	second (mean solar)	+07 3.155 815 0
year (tropical)	second (mean solar)	+07 3.155 692 6
year 1900, tropical, Jan., day 0, hour 12	second (ephemeris)	+07 3.155 692 597 47*
year 1900, tropical, Jan., day 0, hour 12	second	+07 3.155 692 597 47

VISCOSITY

centistoke	meter^2/second	−06 1.00*
stoke	meter^2/second	−04 1.00*
foot^2/second	meter^2/second	−02 9.290 304*
centipoise	newton second/meter^2	−03 1.00*
lbm/foot second	newton second/meter^2	+00 1.488 163 9
lbf second/foot^2	newton second/meter^2	+01 4.788 025 8
poise	newton second/meter^2	−01 1.00*
poundal second/foot^2	newton second/meter^2	+00 1.488 163 9
slug/foot second	newton second/meter^2	+01 4.788 025 8
rhe	meter^2/newton second	+01 1.00*

VOLUME

acre foot	meter^3	+03 1.233 481 837 547 52*
barrel (petroleum, 42 gallons)	meter^3	−01 1.589 873
board foot	meter^3	−03 2.359 737 216*
bushel (U.S.)	meter^3	−02 3.523 907 016 688*
cord	meter^3	+00 3.624 556 3
cup	meter^3	−04 2.365 882 365*
dram (U.S. fluid)	meter^3	−06 3.696 691 195 312 5*
fluid ounce (U.S.)	meter^3	−05 2.957 352 956 25*
foot^3	meter^3	−02 2.831 684 659 2*

To convert from	*to*	*multiply by*
gallon (U.K. liquid)	$meter^3$	−03 4.546 087
gallon (U.S. dry)	$meter^3$	−03 4.404 883 770 86*
gallon (U.S. liquid)	$meter^3$	−03 3.785 411 784*
gill (U K.)	$meter^3$	−04 1.420 652
gill (U.S.)	$meter^3$	−04 1.182 941 2
hogshead (U.S.)	$meter^3$	−01 2.384 809 423 92*
$inch^3$	$meter^3$	−05 1.638 706 4*
liter	$meter^3$	−03 1.00*
ounce (U.S. fluid)	$meter^3$	−05 2.957 352 956 25*
peck (U.S.)	$meter^3$	−03 8.809 767 541 72*
pint (U.S. dry)	$meter^3$	−04 5.506 104 713 575*
pint (U.S. liquid)	$meter^3$	−04 4.731 764 73*
quart (U.S. dry)	$meter^3$	−03 1.101 220 942 715*
quart (U.S. liquid)	$meter^3$	−04 9.463 529 5
stere	$meter^3$	+00 1.00*
tablespoon	$meter^3$	−05 1.478 676 478 125*
teaspoon	$meter^3$	−06 4.928 921 593 75*
ton (register)	$meter^3$	+00 2.831 684 659 2*
$yard^3$	$meter^3$	−01 7.645 548 579 84*

1. Report No. NASA CR-159174	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Technology Requirements for Future Earth-to-Geosynchronous Orbit Transportation Systems - Volume III: Appendices		5. Report Date March 1980
		6. Performing Organization Code
7. Author(s) Vincent A. Caluori, Robert T. Conrad, James C. Jenkins		8. Performing Organization Report No.
		10. Work Unit No. 540-03-13-01
9. Performing Organization Name and Address Boeing Aerospace Company, P. O. Box 3999, Seattle, Washington 98124		11. Contract or Grant No. NAS1-15301
		13. Type of Report and Period Covered Contractor Report Final, Appendices
12. Sponsoring Agency Name and Address National Aeronautics & Space Administration, Washington, DC 20546		14. Sponsoring Agency Code

15. Supplementary Notes

Langley Technical Monitor: Donald G. Eide
Final Report
This report is one of three volumes. The other two are: Volume I - NASA CR-3265 and Volume II - NASA CR-3266.

16. Abstract

Supporting data, in the form of appendices, are documented in this volume to support the final report, Volume II Technical. Appendix A, Engine Data, provides detail technical engine data performed by Aerojet Liquid Rocket Company under subcontract N-500601-9109 to this prime contract. These data are on LOX/CH_4 engine, advanced technology forecast on dual expander engine, integrated thruster assembly (ITA), plug cluster engine (PCE), and propulsion growth. Appendix B summarizes the costing methodology and groundrules. Boeing Parametric Cost Model (PCM) is discussed. It also includes vehicle's WBS dictionary. Appendix C provides the iterative point-design weight estimating methodology used throughout this study as applied to winged launch vehicles. Appendix D presents summary data from the study to evaluate and compare weight data for dedicated and integrated O_2/H_2 subsystems for the SSTO, HLLV and POTV. Detail weights, comparisons, and weight scaling equations are provided.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Engine parametric data. LOX/CH_4 fuel cooled engine concept. LOX/CH_4 hydrogen cooled engine concept. LOX/CH_4 engine; tripopellant dual-expander engine parametric cost model; Vehicle WBS iterative point-design weight estimating dedicated and integrated O_2/H_2 weight data.	Unclassified - Unlimited Subject Category 16

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	143	$7.25

* For sale by the National Technical Information Service, Springfield, Virginia 22161